INNOVATIVE RADIO-FREQUENCY LINEAR ACCELERATING STRUCTURES

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to my mum
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Chapter 1

Introduction

The present thesis work illustrates the Radio-Frequency (RF) design of two innovative linear accelerating structures: a high repetition rate RF Gun and a hybrid compact photoinjector.

An RF Gun is a source of electron beams that are usually used for X-ray production. The reason for choosing this type of Gun, that is laser-driven, instead of thermionic or DC ones, stands in the necessity of generating electron beams that have high peak current, small energy spread and low emittance. The last three beam properties summarize exactly the crucial requirement of the SPARX-FEL project (Sorgente Pulsata Autoamplificata di Radiazione X, i.e. Free Electron Laser): high brightness. An always higher demand of average FEL flux to be achieved at higher repetition rate than in the past makes this type of RF Gun perfectly suitable for the SPARX project. We will discuss the overall performance of this structure assuming a repetition rate of 100 Hz. A major concern for high repetition rates is the average power handling, that requires an intricate cooling system to lower the temperature rise. The introduction of a new machining technique (DMF3), Direct Metal Free Form Fabrication, could allow much higher rep-rates, for example up to 1kHz, making use of an aggressive cooling system. The RF Gun consists of 1.6 cell working at 2.856 GHz (S-band). The RF design is
performed by using the codes HFSS and Superfish as well as the optimization of the main electromagnetic parameters, such as resonant frequency, quality factor and shunt impedance. Both single and dual-feed configurations are examined, following the guidelines of LCLS Gun, at SLAC National Labs. Furthermore, a thorough study of higher order field components is performed, since they are a major cause to degrade FEL performance. Finally, thermal and stress analysis are carried out and the correspondent detuning of the structure is evaluated.

The second RF design that is object of the present thesis is a hybrid compact photoinjector, a novel accelerating structure in the class of photoinjectors. The combination of an RF Gun, standing-wave (SW) section, and a Linac (Linear Accelerator), traveling-wave (TW) section, in the same accelerator makes it an hybrid. The quality of compactness refers to the reduced geometric dimensions, since the project frequency is in the X-band (11.424 GHz). Small device means low costs of fabrication, and at the same time the possibility of producing electron beams with very high brightness is appealing for FEL interdisciplinary research fields, such as biology, medicine, material science and non-linear optics. Furthermore, the hybrid compact photoinjector is suitable for application concerning the production of hard X-rays that are monochromatic, tunable and with a small spot size.
Chapter 2

Linear RF structures

A linear particle accelerator is a radio-frequency device where particle beams, after being generated either by a laser or a thermionic source, travel along a linear path through an array of low-voltage cavities, also called cells. The electromagnetic field in each cell oscillates at frequencies in the MHz or GHz range. The main advantages of linear accelerators can be summarized as follows:

- capability of delivering high energy and focused beams;
- the electric breakdown is not a crucial limiting factor as in old electrostatic accelerators, where the energy beam was only of the order of MeV;
- the possibility of reaching high energy allows a more efficient transverse focusing;
- beam injection and extraction are easier procedures compared with circular machines;
- high frequencies mean very small accelerating devices, since the geometric dimensions are proportional to the wavelength of the electromagnetic field.
2.1 Principi generali di funzionamento

A radio-frequency accelerating structure is usually fed by electromagnetic power generated by a klystron or a magnetron. The RF power is brought to the Linac by a metallic waveguide, through a more or less complicated RF system such as circulators that avoid reflected power to go backwards and harm the source.

1. Traveling-wave (TW) structures

These kind of accelerators are basically RF waveguides where the electromagnetic field travels with a phase velocity equal to the one of the injected beam. Therefore, the beam is locked to the traveling wave with following linear energy gain along the structure. Nevertheless, uniform waveguides are not suitable for such a purpose since any electromagnetic field pattern would always have a phase velocity greater than the speed of light, that means it would never be locked to any particle beam. In order to avoid this issue, it is necessary to load the TW structure with metallic discs along its axis, usually with a certain period \(L\). Figure (2.1) shows such a disc-loaded structure.

![Figure 2.1: Iris-loaded structure](image)

Once the RF power reaches the end of the Linac, it has to be damped in a load whose impedance is matched with the one of the TW structure.
2. Standing-wave (SW) structures

In this case, a number of cavities, cells, are aligned longitudinally and
coupled together either electrically or magnetically. The structure is
closed so that a resonant stationary wave can build up inside it. This
resonant electromagnetic field is trapped inside the Linac and there is
no need to be damped, as in the case of TW Linacs. Therefore, in
theory the input power could all be used to accelerate the beam.

2.2 Characteristic parameters of a Linac

In order to properly understand and be able to choose between a standing-
wave or a traveling-wave structure, we briefly introduce the main parameters
usually used to characterize Linacs ([9], [11], [12]). These parameters are
used to represent accelerating devices by means of electric circuits [7].

1. Shunt impedance per unit length

\[ Z_{SH} = \frac{\bar{E}_0^2}{-\frac{dP}{dz}} \]  

(2.1)

where \( \bar{E}_0 \) is the average value of the axial electric field and \(-dP/dz\)
is the power per unit length dissipated on the metallic walls of the
structure. \( Z_{SH} \) has dimensions of MΩ/m and is twice the value of the
resistor used in the equivalent electric.

2. Quality factor

\[ Q = \omega \frac{w}{-\frac{dP}{dz}} \]  

(2.2)

being \( \omega \) the angular frequency of the RF field and \( w \) the stored energy
in the structure per unit length.
3. **Ratio** $\frac{Z_{SH}}{Q}$

$$\frac{Z_{SH}}{Q} = \frac{\bar{E}_z^2}{\omega w}$$  \hfill (2.3)

This parameter depends only on the geometry of the Linac. It represents the acceleration efficiency of the structure per unit stored energy.

4. **Transit time factor** $T$

$$T = \frac{\int_{-\frac{L}{2}}^{\frac{L}{2}} E(0, z) \cos \left( \frac{2\pi z}{\lambda} \right) dz}{\int_{-\frac{L}{2}}^{\frac{L}{2}} E(0, z) dz}$$ \hfill (2.4)

This parameter allows to take into account the finite velocity of the particle moving through the axis of a cavity with length $L$, where the RF electric field is oscillating according to:

$$E(r = 0, z, t) = E(0, z) \cos (\omega t(z) + \varphi)$$ \hfill (2.5)

where $\varphi$ is the phase of the field with respect to the particle, when it is at the center of the cavity. Since this field oscillates in time, the particle only gains a fraction of the energy it would gain if the axial electric field was constant with a value equal to $E(0, z)$, that is at $t = 0$. The transit time factor $T$ represents exactly this energy fraction.

5. **Effective Shunt Impedance per unit length**

Assuming that the power is uniformly dissipated along the accelerating cavity, the parameter defined in 1) becomes:

$$Z_{SH} = \frac{\bar{E}_0^2}{-\frac{dP}{dz}} = \frac{\bar{E}_0^2}{-\frac{P}{L}} \Rightarrow Z_{SH}T^2 = \frac{(\bar{E}_0 T)^2}{-\frac{P}{L}}$$ \hfill (2.6)

This parameter allows to determine the efficiency of the particle acceleration per unit length.
6. **Frequency**

One of the most important parameters to choose as working point of an accelerating structure is represented by the value of the frequency. This choice depends on the values that the parameters listed above assume at a certain frequency or another. As an example, the shunt impedance \( Z_{SH} \) is proportional to \( \sqrt{\omega} \), that is higher frequencies provide higher efficiency in beam acceleration. Also, the probability of RF breakdowns, due to intense superficial electric fields, diminishes with increasing frequency. This is explained by the Kilpatrick experimental relationship:

\[
f(MHz) = 1.64E_k^2 \exp(-\frac{8.5}{E_k})
\] (2.7)

where \( E_k(\text{MV/m}) \) is called the Kilpatrick field and \( f(\text{MHz}) \) is the frequency of the field. The formula (2.7) establishes an upper limit for the superficial field \( E_k \) at a given frequency. Beyond the Kilpatrick field value, the chance of breakdowns at that frequency starts to rapidly raise, resulting in damages of the material the Linac is made out of. By inverting the expression (2.7) with numerical methods is possible to express \( E_k \) as a function of the frequency \( f \), e.g. \( E_k \) equals 46.8 MV/m for \( f = 3\text{GHz} \). On the other hand, the geometric dimensions of an accelerating structure are inversely proportional to the frequency, so that higher frequencies, meaning smaller Linacs, are not always the best choice due to fabrication issues.

An other parameter used for the Linac RF design is the *Kilpatrick factor* defined as the ratio of the superficial electric field \( E_s \), that the structure can actually support, to the value of the Kilpatrick field for the same frequency. Usually, this ratio is less than 2 although in some cases is possible to reach higher values. Referring to the example above
for a frequency of 3 GHz, it is possible to reach superficial electric fields of about \( E_s = 100 \text{ MV/m} \).

7. **Group velocity** \( v_g \) and **filling time factor** \( t_f \)

\[
v_g = \frac{P}{w} \quad \text{(2.8)}
\]
\[
t_f = \int_0^L \frac{dz}{v_g(z)} \quad \text{(2.9)}
\]

where \( P \) is the power flux through the structure with length \( L \). The stored energy per unit length (\( w \)) is proportional to the square of the power of the accelerating electric field. It is convenient to assume small values of the group velocity, usually the order of \( 0.01c \) to \( 0.02c \), so that the efficiency of acceleration is not reduced drastically and the **filling time factor** is kept within reasonable values. The above formula for \( t_F \), that represents the time the electromagnetic energy needs to fill the whole structure, is only used for traveling-wave accelerators. In the case of standing-wave Linacs, where the electromagnetic energy builds up in time with a zero group velocity, the parameter \( t_F \) is defined as

\[
t_F \propto \frac{Q}{\omega}. \quad \text{(2.10)}
\]

### 2.3 Dispersion Curve

The difference between traveling-wave and standing-wave particle accelerators is not crucial from a theoretical point of view. Indeed, a stationary wave can always be thought as a superposition of waves traveling in opposite directions. In an “iris loaded” structure, see Fig.(2.1), the wave propagation along the axis ia allowed by constructive interference between forward waves and the ones reflected from the irises. It follows that it is possible to
enclose the structure between two metallic plates placed at symmetry plane locations so that the stationary field pattern, at a given time, is the exact representation of the traveling one. In this configuration, it is possible to measure electromagnetic parameters of the TW structure, such as phase or group velocity of the desired accelerating mode and the shunt impedance per unit length, by using the equivalent stationary “instantaneous mode” of \( n \) resonant cavities coupled together. Nevertheless, it must be pointed out that the definition of phase advance of the electromagnetic field is different for the two cases, TW and SW. In a TW Linac, the “phase-shift” is determined by the phase increase, or decrease, of the field traveling from the center of a cell to the subsequent one, while for a SW structure, it refers to the field configuration, since the phase difference is either 0 or \( \pi \). Figure (2.2) shows the dispersion curve for \( n \)-coupled cavities, with \( n = 9 \).

![Figure 2.2: Dispersion curve of a 9 cell cavity](image)
2.4 Comparison of “effective shunt impedance” between TW and SW structures

Figure (2.3) [6] illustrates the behavior of the “shunt impedance” per unit length as a function of different phase shift between each cell. To each phase-shift corresponds a different accelerating mode.

As it is evident, the value of the effective shunt impedance for TW structures is almost twice that for SW accelerators except for the $\pi$ mode in which case the two values match. Another important parameter is the pulse length from the generator that feeds an accelerating structure. In a TW structure, the excited electromagnetic field needs a time $t_F$, the filling time factor defined as $L/V_g$ ($V_g$= group velocity, $L$=length of the Linac) while in a SW structure the field distribution “builds up” in a longer time due to subsequent reflections. It follows that, since the beam is usually injected into the Linac
after the filling time, all the power used for the transient is not used to accelerate it, that means it is lost. Then, it is reasonable that for “long pulse” operation the unused power is small compared to the total RF power, so that the choice of the type of structure only depends on the kind of particle to be accelerated or the desired phase-shift. On the other hand, in “short pulse” operation the lost transient power is a large amount of the total one, so a TW structure, with a small filling time, is preferred to an SW one.

2.5 Periodic Accelerating Structures

In this chapter, we will discuss accelerating structures with cylindrical symmetry and supporting a traveling wave field in $TM_{01}$-like mode. The longitudinal component can be expressed as:

$$E_z = AJ_0(k_{01}r)e^{i(\omega t - k_0 z)}$$

where

$$k_{01} = \frac{2.405}{a}, \quad \frac{\omega^2}{c^2} = k_{01}^2 + K_0^2$$

From Eq.(2.12), it follows that the phase velocity of the traveling wave is

$$v_f = \frac{\omega}{k_0} = \frac{c}{\sqrt{1 - \frac{k_{01}^2 c^2}{\omega^2}}} > c$$

A phase velocity higher that the speed of light doesn’t allow particle acceleration. Therefore, a uniform waveguide is useless. This result is more obvious looking at picture (2.4), where the dashed line refers to the speed of light.

The value of the phase velocity is given by the angular coefficient of the vector starting from the origin of the diagram and ending in any point of the hyperbole, $v_f = \frac{\omega}{k_0}$, while the derivative in any point the curve represents
the group velocity, \( v_g = \frac{d\omega}{dk} \). Also, the diagram is symmetric with respect to origin, that is the wave can be either forward or backward along the \( z \)-axis. In order to decrease the phase velocity of the traveling wave structure, the above mentioned uniform waveguide can be loaded with periodic array of discs along the axis. This kind of structure is known as ”iris-loaded” and it is shown in Fig.(2.1), where \( L \) is the spatial period. The solution of the wave equation for an electromagnetic field inside this kind of structure has to satisfy the following two conditions:

1. Floquet theorem, stating that in a given mode of an infinite periodic structure, the fields at two different cross sections that are separated by one period \( L \) differ only by a complex constant \( e^{-jkoL} \);

2. boundary conditions are not satisfied by only one resonant mode, as in the case of an uniform waveguide, but by a Fourier expansion of space harmonics.

It follows that the field can be expressed as:
\begin{align}
E_z(r, z, t) &= F(r, z)e^{j(\omega t - k_0 z)} \quad (2.14) \\
F(r, z) &= F(r, z + L) \quad (2.15) \\
F(r, z) &= \sum_{n=0}^{\infty} a_n(r)e^{-j(2\pi n z/L)} \quad (2.16)
\end{align}

From the wave equation in cylindrical coordinates and taking into account the 2.14, we obtain:

\[ e^{j\omega t} \sum_{n=-\infty}^{+\infty} e^{-j(k_0 + 2\pi n/L)z} \left[ \frac{d^2a_n(r)}{dr^2} + \frac{1}{r} \frac{da_n(r)}{dr} + K_n^2 a_n(r) \right] = 0 \quad (2.17) \]

where

\[ K_n^2 = \left( \frac{\omega}{c} \right)^2 - \left[ k_0 + \frac{2\pi n}{L} \right]^2. \quad (2.18) \]

We can derive the expression for the phase velocity of the \( n \)-th space harmonic, that is

\[ v_{ph} = \frac{\omega}{k_0 + \frac{2\pi n}{L}} = \frac{\omega}{k_n} \quad (2.19) \]

For all \( n \), each wave propagates with a given \( v_{ph} \) that is lower than a wave in an uniform waveguide. Each iris acts as a scatterer generating a forward and a backward wave. Assuming that the period \( L \) is an integer multiple of half wavelength of the mode, constructive interference builds up inside the structure so that a standing wave is obtained. Thus, the dispersion curve in the loaded waveguide substantially differs from the uniform case. It is always possible to find a value of \( n \) such that, from equation (2.19), one has \( v_{ph} = v_p \), which represents the desired condition in order to accelerate a particle with velocity \( v_p \).

In general, \( v_{ph} < c \) that means \( K^2 < 0 \), so the solution of the Bessel equation (2.17) is given by a modified Bessel function:
\[ a_n(r) = A_n I_0(Kr) \] (2.20)

where \( A_n \) is a constant.

The curve showing the relationship between \( \omega \) and \( k_n \) is sketched in Fig.(2.5)[11], and the analytical expression is the following [7]:

\[ \omega = \frac{2.405c}{b} \left[ 1 + \frac{\kappa}{2} \left( 1 - \cos \psi e^{-\alpha t} \right) \right] \] (2.21)

where

\[ \kappa \equiv \frac{4a^3}{3\pi J_1^2(2.405)b^2L} \] (2.22)

being \( \psi = k_0L \) the cell-to-cell phase shift.

Figure 2.5: Dispersion curve of an “iris-loaded” metallic waveguide.

Some important features to underline about this curve are the following:

(2.5):

- for a given mode, only a finite frequency range is allowed, from \( \omega_c \) to \( \omega_n \) (passband); at both ends of this interval, the group velocity \( v_g = d\omega/dk_n \) is equal to zero;

- for a given frequency, the structure can support an infinite number of space harmonics, from \( n = -\infty \) to \( n = +\infty \); all of these harmonics have the same group velocity but different phase velocities;
whenever the phase and group velocities of a given wave have the same
directions, we talk about a “forward” wave, while in the case of opposite
directions we refer to a “backward” wave.

In Fig. (2.5), the electromagnetic energy propagates in the $+z$ direction
(solid lines). At the end of the cavity this energy can be either terminated
into a matched load or reflected back by a shorting end wall. In the former
case, the propagating mode is transmitted to the load and we talk about a
traveling-wave (TW) structure. In the latter case, the wave is reflected back
and forth giving rise to a resonant field, so that we have a standing-wave (SW)
cavity. Reflected waves are also taken into account in Fig. (2.5), dotted lines.

Once the parameters of the accelerating mode inside the structure are
fixed, i.e. $\omega_0, \psi_0, k_0$ and the particle velocity $v_p$, the length of the single cell
is determined by (2.19):

$$L = \frac{\psi_0 v_p}{\omega_0}.$$  \hspace{1cm} (2.23)

In the case of an accelerating mode with a cell-to-cell phase shift equal
to $2\pi/3$ and relativistic particle velocity $v_p \sim c$, one has:

$$L = \frac{\lambda}{3}. \hspace{1cm} (2.24)$$

TW accelerators are mainly used for relativistic particles, while SW cavities
are preferred for slower particles. This can be easily explained by looking
at the graph in Fig. (2.6) [12]:

- the operation point for TW structures is usually around $A$, that repre-
sents the intersection between the dispersion curve of the traveling-wave
cavity with the one relative to the case $v_{ph} = c$;

- SW structures operate with waves having a cell-to-cell phase shift equal
to 0 or $\pi$ (module $2\pi$, points $B$ and $C$), by definition; these points
correspond to a lower phase velocity and the group velocity is equal to zero, as expected for a resonant cavity.

Figure 2.6: Dispersion curve of an “iris-loaded” loaded metallic waveguide. Phase and group velocity are also illustrated

2.6 Standing-wave Structures

A close inspection of Fig. (2.6) indicates the existence of certain modes with zero group velocity. These modes are stationary electromagnetic fields, also referred to as resonant, since there is no power flow through the structure. This happens for the lowest and highest frequencies of the curve, where we have the condition:

\[
k_n L = N \pi, \quad N = 0, \pm 1.
\]  

(2.25)

This means that the structure modes in standing-wave accelerators are either of type 0 or \( \pi \). In the first case, the electromagnetic field has the same phase in each cell; in the second, there is phase opposition between adjacent cells. Besides the structure modes, each cell is characterized by its own cavity mode, either TE or TM, defined by three subscripts \((m, n, p)\) that for a cylindrical cavity are defined as:
• $m$ is the number of full period field variations azimuthally;

• $n$ is the number of zeroes of the axial field radially;

• $p$ is the number of half-period field variations longitudinally.

As an example, the RF Gun object of this thesis work is a standing-wave accelerating structure operating in the $TM_{010}$-like mode.

2.7 Traveling-wave Structures

The accelerating mode in a traveling-wave Linac is characterized by the principle space harmonic, i.e. $n = 0$. Usually, this kind of structure is designed to operate in the $\pi/2$ or $2\pi/3$ mode (see Fig. (2.6)). Two kinds of TW structure are commonly used: constant-impedance and constant-gradient Linacs. In the former case, the impedance of the structure is kept constant, that is achieved by using uniform cell-to-cell irises; in the latter, the inter-cell coupling holes are adjusted in order to keep a constant value of the accelerating field. In the next section, we will discuss about constant-impedance TW structures since the project of the hybrid compact photoinjector in the present thesis is characterized by that kind of accelerators.

2.7.1 Constant-impedance Linac

A sketch of a constant-impedance TW structure is given in Fig. (2.7). A certain amount of the input power is dissipated, while propagating along the Linac, in the metallic walls. Thus, the resulting electromagnetic field is attenuated:

$$\frac{dE_{z0}(z)}{dz} = -\alpha(z)E_{z0}(z),$$

(2.26)

where $\alpha(z)$ is the attenuation constant. In the same way, we have:
Figure 2.7: Sketch of a constant-impedance TW structure

\[
\frac{dP(z)}{dz} = -2\alpha(z)P(z) \quad (2.27)
\]

and by exploiting the definition of \( Q \) and \( w \), one obtains:

\[
\frac{dP(z)}{dz} = -\frac{w}{Q} \frac{P(z)}{v_g}. \quad (2.28)
\]

It follows, from (2.27) and (2.28), that

\[
\alpha(z) = \frac{w}{2Qv_g(z)}. \quad (2.29)
\]

The geometry of a constant-impedance accelerator is unmodified along the axis, that means:

\[
\alpha(z) = \text{constant} = \alpha \quad \text{and} \quad E_{z0}(z) = E_{z0}e^{-\alpha z}. \quad (2.30)
\]

The energy gain of a particle with a charge \( q \), that is always on crest of the field inside a constant-impedance TW Linacs (length \( L \)) is

\[
qV = \int_0^L E_{z0}e^{-\alpha z}dz = qE_{z0}L \frac{1 - e^{-\alpha L}}{\alpha L}. \quad (2.31)
\]
This expression assumes the maximum value for $\alpha L = 1.26$, i.e.

$$qV_{\max} = 0.57E_{z0}(0)L$$

and at the exit of the accelerator one has:

$$E_{z0}(L) = 0.28E_{z0}(0) \quad \text{e} \quad P(L) = 0.08P(0),$$

that means less than 10% of the input power goes into the matched load.

We need to point out that the radii of the main cells and the geometric dimensions of the inter-cell irises must be chosen accordingly with the desired frequency and mode of operation.
Chapter 3

RF Guns

Radio-Frequency (RF) Guns are devices used for the generation of electron beams. The electron source is represented by the cathode. Its main target is usually to provide high current beams. Moreover, a subsequent, fast acceleration is needed in order to reduce the space-charge forces and preserve the emitted beam quality. The first cathode, vastly used until mid 1980s, was the thermionic gun (still in use), where electrons are generated by thermal escape from the surface of the metal. The progress in manufacturing newer material allowed an increase in the peak current from $\approx 100 \mu A/cm^2$ with refractory metal cathodes up to $\approx 20 A/cm^2$ with modern dispenser cathodes (usually porous tungsten impregnated with a mixture of BaO and $Al_2O_3$), although the quality of the beam in terms of energy spread and emittance never reached the requirements for the most demanding applications. A huge innovation happened with the use of laser-driven photocathode using Radio Frequency (RF) acceleration. Electrons are emitted by photoelectric effect and it is possible to easily obtain high density beams. The peak current can reach values of 100 kA/cm², more than three order of magnitudes higher that the best thermionic guns. The possibility of shaping the laser pulse allows to manipulate the transverse and longitudinal characteristics of the beam. The preservation of the high brightness of the beam is due to the intense RF field
inside the gun, only possible at Radio frequency but not in DC.

### 3.1 Longitudinal Dynamics

![Sketch of an (N + 1/2) cell RF Gun](image)

A sketch of an \((N + 1/2)\) cell RF Gun is shown in figure(3.1) [24], [23]. The RF Gun length is \((N + 1/2)\lambda/2\) and it operates in the \(\pi\)-mode, whose accelerating electric field is given by:

\[
E_z = E_0 \cos(kz) \sin(\omega t + \phi_0) \tag{3.1}
\]

where \(E_0\) is the peak accelerating field, \(\lambda\) is the RF wavelength, \(k = 2\pi/\lambda\), \(c\) is the speed of light, \(\omega = ck\), and \(\phi_0\) is the RF phase of the particle exiting the cathode surface at \(z = 0\) and \(t = 0\).

In order to derive the equations of motions, we introduce the following quantity:

\[
\phi = \omega t - kz + \phi_0 = k \int_0^z \left( \frac{\gamma}{\sqrt{\gamma^2 - 1}} - 1 \right) dz + \phi_0 \tag{3.2}
\]
Here, the following relationships have been employed:

\[
\frac{\gamma}{\sqrt{\gamma^2 - 1}} \approx \frac{1}{\beta} = \left( \frac{1}{c \frac{dz}{dt}} \right)^{-1}
\]  

(3.3)

where the relativistic factor \( \gamma \) is defined as \( \gamma = 1 + W/mc^2 \), being \( W \) and \( mc^2 \) the electron’s relativistic energy and rest energy, respectively. The equation of motion of an electron inside the electric field expressed in Eq.(3.1), is given by:

\[
\frac{d}{dz}(\gamma mc^2) = eE_0 \cos(kz) \sin(\omega t + \phi_0)
\]  

(3.4)

and, by exploiting Eq.(3.2), we obtain:

\[
\frac{d\gamma}{dz} = \frac{eE_0}{2mc^2} [\sin(\phi) + \sin(\phi + 2kz)].
\]  

(3.5)

The second term between the square brackets represents the backward propagating wave. It produces modulation in the energy gain of the particle, and can be neglected only in the case of long accelerating structures where the particles injected are relativistic. In an RF Gun, the speed of the electrons is about zero.

Equations (3.4) and (3.5) are sufficient to completely determine the longitudinal dynamics of electrons in an RF Photoinjector.

A more handful formula can be derived noticing that the integrand function in Eq.(3.2) is significantly larger than zero only near the cathode area, where the electrons are non-relativistic. Thus, in that region \( (z = 0) \), we can substitute Eq.(3.5) with:

\[
\frac{d\gamma}{dz} \approx \frac{eE_0}{2mc^2} \sin(\phi_0).
\]  

(3.6)

so that an approximate expression of \( \gamma, \tilde{\gamma} \), is given by:

\[
\tilde{\gamma} = 1 + 2\alpha kz \sin(\phi_0),
\]  

(3.7)
where

\[ \alpha = \frac{eE_0}{2kmc^2} \]  \hspace{1cm} (3.8)

is a dimensionless parameter, representing the strength of the accelerating electric field. Making use of Eq.(3.7), expression (3.2) can be trivially integrated, leading to the following result:

\[ \phi = \frac{1}{2\alpha \sin(\phi_0)} \left[ \sqrt{\gamma^2 - 1} - (\gamma - 1) \right] + \phi_0. \]  \hspace{1cm} (3.9)

and

\[ \gamma = 1 + \alpha \left\{ k_z \sin(\phi) + \frac{1}{2} \left[ \cos(\phi) - \cos(\phi + 2k_z) \right] \right\}. \]  \hspace{1cm} (3.10)

Equations (3.9) and (3.10) are the approximate solutions of the equations of motions (3.2) and (3.5). In Fig. (3.2) and (3.3), the comparison between the solutions of these equations obtained by numerical calculation and by approximation is shown. The plots assume \( \alpha = 1 \) and two different values of \( \phi \), \( 30^\circ \) and \( 70^\circ \). There is very good agreement for the quantity \( \gamma \), while we observe a good match for the phase \( \phi \) only for \( \phi_0 \) not too small.

One of the main parameters that determines the beam performance throughout the accelerating system is the injection phase \( \phi_0 \) at the cathode in the Gun. In order to derive it, we have to make an assumption for the phase of the beam at the exit of the RF Gun itself (\( \phi_\infty \)). According to the theory of transverse dynamics in RF fields, discussed in the following section, the transverse emittance, that represent a crucial figure of merit of the beam, reaches is minimum for \( \phi_\infty = \pi/2 \). The value of the phase at the exit of the Gun can written as:

\[ \phi \rightarrow \phi_\infty = \frac{1}{2\alpha \sin(\phi_0)} + \phi_0 \]  \hspace{1cm} (3.11)

and, with the result discussed above, we obtain:
Figure 3.2: Plots of $\gamma$: exact solution (solid lines) and approximation (dotted lines)

Figure 3.3: Plots of $\phi$: exact solution (solid lines) and approximation (dotted lines)

\[
\left(\frac{\pi}{2} - \phi_0\right) \sin(\phi_0) = \frac{1}{2\alpha}.
\] (3.12)
3.2 Longitudinal and Transverse Dynamics in RF Guns

The longitudinal phase space is described by the pair \((z, p_z)\), where \(z\) is the longitudinal position and \(p_z\) the dimensionless longitudinal momentum defined as

\[
p_z = \beta \gamma
\] (3.13)

It has to be noticed that after acceleration \(p_z \approx \gamma\), since \(\beta \approx 1\). The spread in the phase \(\Delta \phi\) is related to the spread of the longitudinal position by \(\Delta \phi = -k \Delta z\). This means that particles with positive \(\Delta \phi\) are located in the tail of the electron bunch relative to those with negative \(\Delta \phi\).

Considering Eq.(3.11), we can define the asymptotic bunch compression factor

\[
\frac{\Delta \phi_\infty}{\Delta \phi_0} = 1 - \frac{\cos(\phi_0)}{2\alpha \sin^2(\phi_0)}
\] (3.14)

Therefore, bunches that undergo acceleration are simultaneously compressed in length. This phenomenon is known as “longitudinal RF focusing”.

In the case of relativistic electrons and assuming an ideal, infinite accelerator, the transverse RF forces are negligible. On the other hand, inside an RF Gun, where electrons leave the cathode surface with a very low energy, usually 1 eV, these forces are not negligible. In particular, entering the region of the cell-to-cell iris, electrons undergo defocusing RF forces. At the exit of this region, the forces are focusing and if a good field balance is achieved, i.e. the field amplitudes in the Gun cells are equal at any time, then the total transverse force is zero. Nevertheless, at the exit of the Gun the field is only at one side of the iris so that the electrons receives a net transverse deflection, known as “exit-kick”. In Fig. (3.4a), the inter-cell iris is shown.
along with electric field lines, while the electron trajectories are plotted in Fig. (3.4b).

![Electric Field lines and Electron Trajectories](image)

**Figure 3.4: a) Electric Field lines; b) Electron trajectories**

The expression for the radial momentum variation of the electrons exiting the structure can be easily derived and it is equal to:

$$\Delta p_r = \alpha kr \sin(\phi_{\infty}), \quad (3.15)$$

where we assumed a relativistic velocity for the particles ($\beta \approx 1$), as it realistically happens at the Gun exit. Translating expression (3.15) into cartesian coordinates, one has:

$$\Delta p_x = (\alpha k \sin(\phi_{\infty}))x. \quad (3.16)$$

The quality of the beam is usually described by a factor famous in literature as “normalized emittance” $\epsilon_x$, defined as:

$$\epsilon_x = \sqrt{<p_x^2> <x^2> - <p_x x>^2}. \quad (3.17)$$

A good beam performance implies a small value for the emittance. It can be demonstrated that the minimum value is obtained for $\phi_{\infty} = \pi/2$ and, for a Gaussian beam, it is equal to:
\[ \epsilon_x = \frac{\alpha k < x^2 > \sigma_{\phi}^2}{\sqrt{2}}. \]  

(3.18)

By looking at Eq. (3.15), it is evident that a minimum for the transverse emittance corresponds to the maximum transverse kick. This is one of the main reason why a magnetic solenoid is needed around the RF Gun.
Chapter 4

RF Gun for the Sparx project

The peak electron beam brightness of the SPARX project at the LNF-INFN (in collaboration with ENEA, CNR and University of Rome “Tor Vergata”) is a crucial requirement, one which in order to meet the demands of average FEL flux should also be achieved at a higher repetition rate than in the past. A sketch of the SPARX layout is shown in Fig. (4.1).

Figure 4.1: Sketch of SPARX layout.

The beam brightness $B$ is defined as:

$$B \propto \frac{I}{\epsilon_x \epsilon_y},$$  \hspace{1cm} (4.1)

where $I$ is the beam current and $\epsilon$ the transverse emittance. It follows that the main requirements for FEL operation are:
1. High peak current
2. Small energy spread
3. Low emittance.

To this end, a 1.6 cell RF Gun working in S-band with a 100 Hz repetition rate has been studied and designed while balancing optimization of the RF parameters and the beam dynamics requirements. The RF design has been carried out using the 2D and 3D modeling codes SUPERFISH [3] and HFSS [1], respectively. In sections (4.1) through (4.8), we present the design of a dual-feed Gun, following the guidelines of LCLS while from section (4.9) a single feed Gun is discussed. In both cases, dual and single-feed, electromagnetic field multipole components inside the gun have been shown to contribute to beam emittance growth [15], resulting in beam brightness decrease and concomitant degradation of FEL performance. The dipole field component is completely eliminated by using a dual feed system of external coupling to the waveguide, while a ”race track” geometry is exploited in order to strongly decrease the quadrupole mode. The minimization of the quadrupole transverse magnetic field components, which are the ones to couple most strongly to the beam dynamics, has been considered as the figure of merit in the design optimization process. This race-track geometry is naturally suited to the external coupling employed in the gun, which differs from that used, e.g., on the SPARC injector. This external coupling optimization, which must be set also considering the possibility of beam loading derived power losses, has been performed, with the proper coupling coefficient simulated in HFSS. Further, couplers represent critical area for both RF heating and related thermal stress and breakdown problems, since they are the region where surface RF magnetic fields reach their maximum value in the structure. Thus the RF dissipation, along with the narrowness of the copper in the vicinity, causes large temper-
ature rise, a phenomenon referred to as “RF pulsed heating” [20], [14]. The irises themselves are areas where the surface electric field is locally intense. Thus, in order to mitigate possible breakdown, a thorough study of the iris shape choice on the electric field has been carried out. Additionally, the cell-to-cell iris thickness and radius has been chosen to achieve a high enough value of frequency difference between the two gun coupled resonant modes (0 and $\pi$). With this design in hand, a transient analysis of the RF gun response has also been carried out, allowing a comparison of the simulated fill-time with theoretical prediction. Similarly the RF model of the gun is employed in the code PARMELA [3] to allow preliminary beam dynamics simulations. Finally, and most critically for the purpose of understanding the maximum repetition rate of the gun itself, thermal and stress analyses of the cavity are carried out by using the code ePhysics [2]. We have studied several geometries, for cooling channels, including a novel channel shape that is allowed only using advanced conformal fabrication techniques. These techniques, typified by using Direct Metal Free Form Fabrication (DMF3), are seen to yield qualitatively and quantitatively superior cooling efficiency. In addition to cooling channels, we have also taken into account the need to make the structure more mechanically robust, so that thermal stresses that still result after optimization of the cooling are managed as well as possible. This analysis approach, taken in tandem with a perturbative calculation of the cavity response in the presence of thermo-mechanical deformations, allows us to predict the adequacy of this RF, thermal and mechanical design for repetition rates well in excess of the peak foreseen in the context of SPARX, 100 Hz.
4.1 RF Design (Dual-Feed)

The RF gun cavity consists of one full cell (half-wavelength), and an upstream cathode cell of relative length 0.6 compared to the full cell. The electromagnetic field inside the structure is excited by a dual RF feed power that flows into the full cell through two identical ports, 180° in opposition to each other. The 3D model of the structure is shown in Fig.(4.2). A structure with this symmetry by design causes the dipole field component of the excited mode to vanish, while the dual feeding cancels the transient part of the RF dipole. Moreover, a race-track geometry has been designed in order to minimize the quadrupole component of the field, with the results discussed in Section (4.4). Higher order modes quadrupole may be considered negligible.

![Figure 4.2: 3D Model of the dual-feed RF Gun, from HFSS.](image)

As shown in Fig.4.2, the geometry chosen for the coupling slots, or coupling windows, is based on ”Z-coupling” design (details in section(4.3)) with ”fat-lip” rounded edges. Basically, ”Z-coupling” refers to the use of only one dimension, along Z-axis, for the coupling slot. This has the main purpose to
reduce the temperature rise at the power-coupling ports due intense magnetic field. The "fat-lip" rounding allows to decrease the temperature gradient rise and to keep it below a critical upper limit (60°C for S-band operation). The simulation code used for the electromagnetic design of the RF is HFSS (High Frequency Structures Simulator). The final dimensions of the RF Gun are given in Figure (4.3), with a close-up of the rounded coupling window.

Figure 4.3: (above) One-quarter section of the RF gun with all the geometric dimensions indicated; (below) close-up of the coupling window, with dimensions.

The main electromagnetic parameters of the RF Gun are listed in Table (4.1).

The operation electromagnetic field inside the cavity is a \( \pi \)-mode reso-
nant at 2.856 GHz. It has a quality factor $Q_0$ of about 13,500. The mode separation between the 0 and $\pi$-mode is approximately 15 MHz. The value of the coupling coefficient $\beta$ is chosen from beam loading considerations (see Section (4.2)). Figure (4.4) shows the plots of the amplitude and phase of the axial electric field. At the cathode position, the electric field peak is nearly 120 MV/m for 10 MW input RF power.

![Figure 4.4: amplitude and phase profiles of the electric field along the gun z-axis.](image)

We note that excellent beam performance is also expected at 100-110

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_\pi$</td>
<td>2.856 GHz</td>
</tr>
<tr>
<td>$\Delta f = f_\pi - f_0$</td>
<td>15 MHz</td>
</tr>
<tr>
<td>$\beta$</td>
<td>1.17</td>
</tr>
<tr>
<td>$Q_0$</td>
<td>13500</td>
</tr>
<tr>
<td>$Q_{ext}$</td>
<td>11490</td>
</tr>
<tr>
<td>$R_s/Q_0$</td>
<td>3.63 k$\Omega$/m</td>
</tr>
<tr>
<td>$E_{peak}$</td>
<td>120 MV/m @ $P_{RF}=10$MW</td>
</tr>
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</table>

Table 4.1: Main RF Gun Parameters.
MV/m peak field operation, allowing one to consider peak powers in the approximate range of 7-8.5 MW in the case of very high repetition rate operation. On the other hand, for highest field operation, one must consider the maximum power case. By plotting the electric field on all the gun surfaces obtained from the 2D-code SUPERFISH, as shown in Fig. (4.5a), it is evident that the irises are potentially critical areas (in particular that connecting the 0.6 and the full cell), where the E-field, with a peak of 130MV/m, exceeds that on the cathode. In S-band structures, the value that is generally considered the safety upper limit for avoiding breakdowns is about 100 MV/m. In order to reduce the surface electric field, elliptical irises have been used instead of circular. In Fig. (4.5b), irises have elliptical shapes (a=0.8cm, b=1.1cm). The peak surface E-field is nearly 10% lower than the previous case and the frequency difference between the two Gun resonant modes increases from 14 MHz to 20 MHz. In this new configuration, the average electric field increases, but the variation diminishes, simultaneously mitigating the RF dissipation and breakdown concerns.

Another geometric parameter that contributes to the mode separation is the inner radius of the cell-to-cell iris. In Fig. (4.6), the same configuration as in Fig. (4.5b) with ag=1.585cm is shown. It can be seen that even though the E-field peak is slightly affected, the mode separation in this case is nearly 26 MHz.

Since the use of elliptical irises as well as the change of the irises thickness and radius obviously cause the resonance frequency of the structure to vary, the half cell and full cell radii have been modified in order to keep the mode resonant at 2.856 GHz. In Table 4.2, the three cases explained above are listed, with particular attention to the peak of the electric field values and mode separations.
Figure 4.5: Peak surface E-field along the gun surfaces with a) circular irises and b) elliptical irises.

<table>
<thead>
<tr>
<th>a</th>
<th>b</th>
<th>t=2a</th>
<th>ag</th>
<th>ac</th>
<th>Rh</th>
<th>Rf</th>
<th>E_{peak}(iris)</th>
<th>Δf(0−π)</th>
</tr>
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<tbody>
<tr>
<td>0.9525</td>
<td>0.9525</td>
<td>1.905</td>
<td>1.485</td>
<td>1.485</td>
<td>4.219</td>
<td>4.2665</td>
<td>130</td>
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<td>1.485</td>
<td>1.485</td>
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<td>4.253</td>
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<td>20</td>
</tr>
<tr>
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<td>4.239</td>
<td>4.269</td>
<td>117</td>
<td>26</td>
</tr>
</tbody>
</table>

Table 4.2: Peak surface electric field on the iris between the two cells, for different geometric parameters, and the correspondent frequency separation between the two gun resonant modes, with cathode electric field kept at 120 MV/m and π-mode frequency at 2856 MHz.

4.2 Coupling and Beam Loading

The waveguide-to-coupler-cell iris dimensions are chosen in order to achieve the value of the coupling coefficient set by potential beam loading considerations (explained below in this section), in which one may allow operation at an average extracted beam power, near RF flat-top, of 1.4 MW (aver-
age current of 286 mA, or 1 nC every 10 RF periods). The phenomenon of “Beam-loading” refers to the effects of the beam on the cavity fields. This is particularly the case of high current beams or multi-bunch operation when the beam not only acts as a medium which absorb radio-frequency energy and adds an additional resistive load to the cavity but it is equivalent to a generator, which can either absorb or deliver energy to the cavity modes. This phenomenon is the cause of power reflected back to the generator, in the presence of the beam, and at the same time the nominal value of the accelerating gradient is decreased. According to this explanation, it is possible to represent the beam as an actual current generator in a lumped electrical circuit, where the cavity is described by a parallel RLC. In this scenario, it turns out that the RF parameter able to take into account the effect of “Beam-loading” is the coupling coefficient. From the conservation of energy, one may derive a optimum condition for $\beta$ in order to obtain zero reflection of power from the accelerating structure toward the generator [7]:

Figure 4.6: Peak $E$-field along the gun surfaces, with elliptical irises.
\[
\beta = 1 + \frac{P_b}{P_c},
\]

(4.2)

where \(P_b\) and \(P_c\) are the beam average power and the cavity average power, respectively. By comparing the power lost to beam acceleration and that dissipated in the cavity wall, an estimate of the external coupling coefficient is \(\beta = 1.17\). The parameters of the 2.856 GHz high power RF system feeding the gun and the relevant beam parameters are listed in Table 4.3. Figure (4.7) is a sketch of the pulse timing for the RF power and the electron bunches.

Figure 4.7: Sketch of the pulse timing for the RF power and the electron bunches.

4.3 RF Pulsed Heating

RF Pulsed Heating is a process by which a metal is heated from magnetic fields on its surface due to high RF power [14]. The basic mechanism is the
\[ f_{RF} = 1/T_{RF}\text{ (repetition rate)} \]
\[ \tau_{RF}\text{ (pulselength)} \]
\[ DC_{RF}\text{ (pulsetrain duty cycle)} \]
\[ P_{RF}\text{ (peak power)} \]
\[ f_b\text{ (beam frequency)} \]
\[ \tau_b\text{ (beamlength)} \]
\[ DC_b\text{ (beam duty cycle)} \]
\[ Q_b\text{ (beam charge)} \]

<table>
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</tr>
<tr>
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</tr>
<tr>
<td>[ P_{RF} ]</td>
<td>10 MW</td>
</tr>
<tr>
<td>[ f_b ]</td>
<td>300 MHz</td>
</tr>
<tr>
<td>[ \tau_b ]</td>
<td>10 ps</td>
</tr>
<tr>
<td>[ DC_b ]</td>
<td>3 \times 10^{-3}</td>
</tr>
<tr>
<td>[ Q_b ]</td>
<td>1 nC</td>
</tr>
</tbody>
</table>

Table 4.3: RF feeding system and beam parameters.

local Joule heating generating from the eddy currents that magnetic fields induce on the metal. As a consequence, thermal stresses are induced in the metal. This is a transient process, that means it is due to the oscillating nature of the field. Stresses are caused by the change of the time-varying field intensity that is faster than the time the material expansion, limited in time by the velocity of sound in the material. There is a threshold for the induced stress, proportional to the magnetic field amplitude, beyond which these thermal stresses become thermal fatigues. This limit is known as yield strength and above it micro-cracks and surface roughening eventually occur.

As a consequence, the limit in the surface magnetic field results in a limit in the electric gradient \[ G\text{ (MV/m)} \]. RF pulsed heating is one of the main limiting factors together with the processes of RF breakdowns and dark current trapping. RF breakdowns are due to the emission of absorbed gas from the surface of the metal into the high-power vacuum device. This process results in pulse shortening and high-power spikes. The phenomenon of dark currents is caused by field emitted electrons at the surface of the metal that are accelerated together with the main beam. These three processes are related to the maximum field gradients mainly according to experimental
scaling laws that we represent with a useful plot (Fig.(4.8)).

It is critical to minimize the RF heating of the metal surfaces in the gun in order to allow 100 Hz or higher operation. The limiting sector of the structure is apparently found at the edges of the power-coupling ports. In order to keep the temperature rise below 60°C, rounded coupling iris shapes have been used. Moreover, the use of a Z-coupling geometry simplifies fabrication and reduces pulsed heating since edges are only along one dimension (see Figures 1 and 2), and the narrow copper regions found in θ-coupling (as used in previous UCLA guns) are avoided. The rounding radius of the Z-coupling iris is 1.5mm. In order to quantify the temperature rise, a useful formula [20],[14] is employed:

\[
\Delta T = \frac{|H_\parallel|^2 \sqrt{\tau_{RF}}}{\sigma \delta \sqrt{\pi \rho' c_v k}}
\]  

(4.3)

where \(\tau_{RF}\) is the pulse length, \(\sigma\) is the electrical conductivity, \(\delta\) is the skin depth, \(\rho'\) is the density, \(c_v\) is the specific heat and \(k\) is the thermal
conductivity of the metal. In present case, the value of $H_{||}$ is obtained by plotting the $H$-field obtained from simulations, on all the surfaces of the RF gun. As expected, the critical areas are the coupling windows, where the magnetic field reaches a peak equal to $H_{\text{max}} = 3.9 \times 10^5$ A/m for an input RF power of 10 MW. This field value causes a temperature gradient of about 56° C, a little below the threshold of 60° C, which is considered a sensible upper limit. Problems may arise if the power is significantly higher than 10 MW.

4.4 Magnetic Quadrupole Component

The azimuthal asymmetry in the geometry of the full cell of the gun results in a modification of the field distribution inside. We already discussed the first higher component in section (4.1), the dipole mode, leading to the conclusion that, due to the dual symmetric coupling ports, it vanishes. On the other hand, it is not possible to neglect the quadrupole component. In particular, the field component the most sensitive to this asymmetry is the azimuthal magnetic field $H_{\phi}$. Therefore a thorough study has been performed in order to quantify the deviations of the $H$-field from the monopole behavior. According to experimental results [15], a way to decrease the quadrupole mode is to introduce a geometry perturbation along the axis perpendicular to the beam axis. This technique is called ”race-track geometry” and consists in drifting apart the two arcs of the full cell, so that they have different centers with an offset $D$, as illustrated in Fig.(4.9).

To examine the quadrupole component of the magnetic field, a quarter section of the structure has been simulated, since HFSS allows exploitation of the symmetries of the field inside the gun. Always in Fig.(4.9), a cross-section of the full cell is shown and the field is calculated along circumferences (from 0° to 90°) with different radii $R$ and for different values of the offset $D$, by
which the two cell arcs are drifted apart.

Figure 4.9: Cross-section of the full cell: D is the offset and R is the radius of axis concentric circumferences.

The field component $H_\varphi(r, \varphi)$ is a $2\pi$-periodic function of $\varphi$. Also, it is real and even, thus it can be expanded as a Fourier series of cosine functions:

$$H_\varphi(r, \varphi) = \sum_{n=0}^{\infty} H_{\varphi n}(r) \cos(n\varphi)$$

(4.4)

where the terms $H_{\varphi n}$, that represent the azimuthal magnetic field components, are equal to

$$H_{\varphi n}(r) = \frac{2}{\pi} \int_{0}^{\pi} H_\varphi(r, \varphi) \cos(n\varphi) d\varphi$$

(4.5)

For different values of $n$, we obtain all of the components of the magnetic field:
\[ n = 0 \Rightarrow H_{\varphi 0}(r) = H_M(r) \]  
\[ n = 1 \Rightarrow H_{\varphi 1}(r) = H_D(r) \]  
\[ n = 2 \Rightarrow H_{\varphi 2}(r) = H_Q(r). \]  

where \( H_M(r) \) is the monopole, \( H_D(r) \) the dipole, and \( H_Q(r) \) the quadrupole component, respectively. As noted above, since \( H_{\varphi}(r, \varphi) \) is an even function also in the interval \( 0 < \varphi < \pi \), one directly obtains \( H_D(r) = 0 \), that is the dipole component of the field is eliminate because of the dual feed symmetry.

If the mesh density in the region very near the axis of the gun is small, then it is very difficult to obtain an accurate \( H_{\varphi}(r, \varphi) \) profile. In order to overcome this problem, three values of \( r \) (10, 13, 17 mm) have been chosen and a fit has been made to obtain \( H_2 \) near the axis \( (r=0\text{mm}) \). The quadrupole component of the magnetic field, by linear interpolation, is shown in Fig.(4.10) for different values of \( D \) (0, 1, 2, 3 mm). It is clear that the optimum for the value of the offset \( D \) is approximately 2 mm, where tends towards vanishing.

### 4.5 Transient Analysis

A transient analysis has been performed on the gun response to the RF pulse generated from the klystron. For this study, we have chosen a total pulse length of 4 \( \mu \text{s} \), with (linear) rise and fall times both equal to 0.3\( \mu \text{s} \). In order to get the cavity response, the shunt impedance as a function of frequency has been imported into MATLAB from the simulations run with HFSS. In Fig.(4.11), the envelope of the RF voltage pulse (in red) and the envelope of the cavity response (in blue) are plotted, as functions of time. There is good agreement between the simulated fill time factor and its theoretical value \( (t_F = 700\text{ns}) \).
Figure 4.10: Magnetic quadrupole component for four values of the offset $D$ ($0, 1, 2, 3\text{mm}$).

Figure 4.11: Envelope of the pulse (in red) and envelope of the cavity response (in blue)

### 4.6 Beam dynamics Results

Beam dynamics simulations using the code PARMELA have been performed. The 2D electromagnetic field distribution given as input to PARMELA is
exported from SUPERFISH. The RF gun is examined with a solenoid around it to provide beam size control and emittance compensation. Considering the beam parameters listed in Table 4.3 (beam charge $Q=1$ nC, average beam current $\bar{I}=0.286$ A) and a flat-top bunch, the average energy gain of the electrons at the end of the RF gun is about 5.5 MeV with an energy spread equal to 0.25%. In Fig.(4.12), we plot of the evolution of the electron beam energy gain (in red) along the z-axis, from the cathode position to the exit of the gun. In the same plot, the blue line represents the energy gain derivative with respect to the position: it is evident that it is proportional to the axial electric field, as expected. Simulations of the precise behavior of the beam’s emittance evolution and post-acceleration in a travelling wave linac, are to be performed in order to have a complete dynamics analysis.

4.7 Thermal Analysis

The thermal analysis of the 100 Hz RF Gun has been carried out by using ePhysics2 (see Chapter 6 for details about the code). The aim of the present analysis is mainly to compare different ways to cool the Gun structure, made out of copper and operating at high average power, by using two cooling systems, a conventional and an innovative one. A conventional system is characterized by the use of cooling channels with a cylindrical or rectangular cross-section drilled through the metal either straight and parallel to the beam axis or around the axis in a cylindrical symmetry. This kind of system is standard and well established in the accelerator machining. A novel metal fabrication [17], known as DMF3, Direct Metal Free Form Fabrication, consists in the use of an electron beam to melt metal powder in a layer-by-layer fashion. The DMF3 process allows to obtain fully dense metal parts and is being explored as a way to fabricate internal cooling passages in RF photoinjectors.
Figure 4.12: *Average beam energy gain along the axis (red) and its derivative with respect to the position z (blue).*

A quarter-section of the RF Gun, with standard cooling channels, is shown in Fig.(4.13). Note that mechanisms, tuners, for frequency tuning of each cell are also displayed. To provide cooling, there are six axisymmetric channels and four around the coupling iris region. The circular cross-section diameter is 6 mm in this fairly standard geometry (which might have a rectangular cross-section to be machinable). In order to keep the peak temperature be-
low a certain value, the location of the channels must be optimized. This optimization is achieved by simulating the surface power loss (proportional to $H^2$) effects. The average power inside the gun is 3 kW, considering the power source parameters in Table 4.3 for a 100 Hz repetition rate. The calculation of the (RF dissipated) heat flux inside and outside the RF gun is performed by assuming two different thermal boundary conditions, corresponding to the two different heat transport mechanisms operating on the copper structure:

- Free (natural) convection on the copper outer walls, with a room temperature of $24^\circ$C;
- Forced convection on the channels walls, considering an input water temperature of $24^\circ$C flowing with a velocity of 4 m/sec.

The temperature profile on the inner cavity walls for a dissipated average power of about 3 kW is plotted in Fig. (4.13). The hottest spot of about $53^\circ$C is located at the coupling window, as expected due to the high surface magnetic field. In order to illustrate what improvements can be obtained by using the novel DMF3 process, we show channels with cross-sections that have a star shape (see Fig. (4.14)). This type of channels, which may not be fabricated using standard machining, acts to increase the heat transfer between water and copper, by both increasing the transfer surface and by potentially provoking higher turbulence in the water flow. In choosing the flow rate in the simulations, we have balanced this enhanced thermal efficiency with the prospect of mechanical degradation of the channels due to the enhanced turbulence. The star-shaped cross section allows the cavity wall temperatures to be kept significantly lower than case with cylindrical channels, by $15^\circ$C (see Fig. (4.15)).

It is possible to consider, with such novel fabrication approaches, great improvements in the overall repetition rate. We further optimize the cooling by using a snake-like channel near the coupling irises, as shown in Fig. (4.16).
Figure 4.13: Average beam energy gain along the axis (red) and its derivative with respect to the position z (blue).

In this case, the peak temperature is diminished to 50°C. Thus, considering the same overall temperature increase, this result immediately yields the possibility of a 170 Hz repetition rate. If we further consider a lower peak accelerating field (than 120 MV/m) operation, we deduce that, using our somewhat conservative design criteria, one may achieve 245 Hz operation. With further refinements in the cooling channel design, as well as the mechanical robustness of the structure as a whole, one may anticipate significant further improvements, as discussed below.
4.8 Stress Analysis

The heating of the RF Gun, due to high repetition rate and so high average power, produces thermal stress inside the metal that needs to be concerned about. Thus, we have carried out a stress analysis of the structure by using
the code ePhysics2, considering the case with more standard cylindrical channels as well as that with the star-shaped channels. Due to the temperature increase of the copper and the presence of the cooling channels, the entire structure undergoes a mechanical deformation, which results in detuning of the RF resonance. In the first case, for an average input power of 3 kW and considering the cathode plate and the waveguide sides fixed, and zero deflection where external clamps are present, a peak displacement of about $32\mu m$ is located at the coupling window and on the sides of the full cell. The deformed structure is shown in Fig.(4.17).

By using the Slater perturbation theory, which relates the lost or gained volume and the relative electric and magnetic energy densities to the overall frequency shift of the mode in question, we deduce a detuning in the standard case nearly +350 kHz. This is relatively small, corresponding to a change in nominal operating cooling water temperature of approximately 8° C, which
is only $\sim 60\%$ of the maximum allotted LCLS gun temperature change from the no-RF to full power operation condition. Thus, using the LCLS design philosophy as a guideline, one may also consider augmenting the average power by approximately 1.62. This implies that the repetition rate envelope that we may infer rises to $\sim 400$ Hz. We note that the total frequency shift condition obtained from this analysis is also is sufficient to guarantee that, particularly given the forgiving nature of the high cell-to-cell coupling, the full-to-0.6 cell field balance is not notably changed by thermo-mechanical structure distortions.

In the second case, for an average input power of 5 kW and also considering the cathode plate and the waveguide sides fixed and zero deflection where clamps are present, the peak displacement is similar to the case of standard cooling (see Fig. (4.18)). Thus, concerning mechanical deformation, star-shaped channels allow to use higher RF drive power. We are continuing the study of this structure, as well as the cooling channel with the snake-like shape, to further optimize its performance.
4.9 RF Design (Single-Feed)

In this section, we discuss the design of an RF Gun that still keeps exactly the same electromagnetic properties of the one with dual-feed widely presented in the previous sections but the feeding system is single input, as shown in Fig.(4.19). It might represent the actual photoinjector thought for the SPARX project. A single-feed configuration allows the use of a simpler RF power system than the case of dual-feed and to avoid the possibility of phase shift between the two input waves. The resonant electromagnetic field is always a $\pi$-mode at 2.856 GHz with a quality factor $Q=13,500$. The other main electromagnetic parameters are the same listed in Table 4.1.

The possibility of using only one input waveguide is achieved by means of a dummy waveguide on the opposite side. We refer to it as a “dummy” waveguide since it is above cut-off so that it prevents the power from propagating downward. The only purpose of the dummy waveguide is symmetrization, that is minimization of the dipole mode. To this end, its coupling slot has the same geometric dimensions as the input one. The electromagnetic mode inside the structure, as a resonant field, is not affected by the number of
sources so it doesn’t undergo any change, with respect to the one in the dual-feed, due to only one input. Nevertheless, a strict symmetry is required in the region closely surrounding the full cell in order to keep the dipole field component as low as possible. As far as the quadrupole field component is concerned, a “race-track” geometry has been used, as discussed in Section 4.4, and the optimum value of the off-set D has been estimated.

Figure (4.20) shows the mechanical drawings of the single-feed RF Gun for the prototype fabrication.

### 4.10 Experimental results

Low-power RF characterization of the Gun prototype has been performed at UCLA labs. The accelerating structure is made out of aluminum while copper has been used for the input waveguide, as shown in Fig.(4.21). The full and half cell are machined separately, and clamped together by using
two extra metallic discs and four longitudinal metal rods. The cathode plate is screwed on the half cell contact surface. No brazing process is required
for the prototype at this stage. Also, two tuners are present on each cell, in order to balance the field amplitude. The main RF parameters have been measured by using a Vector Network Analyzer (VNA). The VNA is a device used for measurement in the radio-frequency range of any kind of N-port networks. It allows to obtain the coefficients of the S-Matrix of the device under test. The experimental setup is shown in Fig.(4.22). The low RF input power is fed to the Gun through a standard S-band copper waveguide. All the main electromagnetic properties of the structure are derived from the quantity measurable with the VNA, the reflection coefficient. In Table 4.4, we report a list of the measurements of the RF parameters of the Gun along with a comparison with the results obtained from simulations with the code HFSS.

<table>
<thead>
<tr>
<th></th>
<th>Measurements</th>
<th>Simulations</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_\pi$</td>
<td>2.852 GHz</td>
<td>2.856 GHz</td>
</tr>
<tr>
<td>$f_\pi - f_0$</td>
<td>14.5 MHz</td>
<td>15 MHz</td>
</tr>
<tr>
<td>$Q_0$</td>
<td>10700</td>
<td>13500</td>
</tr>
<tr>
<td>$\beta$</td>
<td>0.5</td>
<td>1.17</td>
</tr>
</tbody>
</table>

Table 4.4: Comparison between measured and simulated RF Gun Parameters

As it is evident, a frequency shift of about 4 MHz between the measured and simulated resonant $\pi$-mode is observed. This is caused by some factors that cause the prototype setup to differ from the simulations. For example, the cold test has been performed in air instead of vacuum, that is likely to cause a frequency shift of 1-2 MHz. Also, humidity can produce a shift of about 0.5 MHz, and the structure is not brazed, leading to the possibility of loose RF contacts. Especially brazing could have caused a lower $Q$, but still reasonably close to the simulated one. The structure results to be undercoupled ($\beta = 0.5$). Low coupling could be caused by mismatching between the
input waveguide and the coupler cell.

Figure 4.22: Experimental setup: RF Gun prototype and VNA.

Figure 4.23: Bead-drop setup

In order to quantify the electric field on-axis, bead-drop measurements have been performed. A small metallic bead, approximately 1 mm in diameter, is attached to a fishing line and slowly dropped down the RF Gun axis,
from the beam tube to the cathode plate. For each step down, a frequency variation of the resonant $\pi$-mode, that is $\omega_\pi$, is observed and recorded using the VNA. A sketch of the bead-drop setup is given in Fig.(4.23). After collecting the data, it has been possible to plot the electric field by applying the Slater perturbation method:

$$|E|^2 = - \left( \frac{4U_0}{3\epsilon_0 \Delta V} \right) \frac{\Delta \omega_\pi}{\omega_\pi} \quad (4.9)$$

where $U_0$ is the total stored energy, given in terms of the unperturbed field, and $\Delta V$ is the volume of the small bead.

Figure 4.24: *Comparison between measured (red dots) and simulated (blue line) axial electric field*

The results plotted in Fig.(4.24) show good agreement between measurements and simulations. It is important to notice that the electric field observed at the very proximity of the cathode assumes higher values than what expected from the simulations. That could be explained by the fact that the bead, approaching towards the cathode plate, causes repulsions forces, consequence of image charges, and therefore an electric field rise. This can also be seen as a capacitive effect.
Chapter 5

Hybrid Compact Photoinjector

5.1 Applications of electron beams

Electron beams and beam induced radiation have a fundamental role in many medical and industrial applications.

<table>
<thead>
<tr>
<th>Sources</th>
<th>Characteristic Energy (MeV)</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>ELECTRONS</td>
<td>0.0001 ⇔ 0.2</td>
<td>Electron tubes</td>
</tr>
<tr>
<td></td>
<td>0.03 ⇔ 0.2</td>
<td>Microwave Instrumentation</td>
</tr>
<tr>
<td></td>
<td>0.01 ⇔ 0.025</td>
<td>Cathode ray tubes</td>
</tr>
<tr>
<td></td>
<td>0.02</td>
<td>Lithography</td>
</tr>
<tr>
<td></td>
<td>0.1 ⇔ 0.3</td>
<td>Laser ionization</td>
</tr>
<tr>
<td></td>
<td>0.05 ⇔ 0.1</td>
<td>Electronic microscope</td>
</tr>
<tr>
<td></td>
<td>0.03 ⇔ 0.3</td>
<td>Metal surface handling</td>
</tr>
<tr>
<td></td>
<td>0.15 ⇔ 10</td>
<td>Radiochemical and radiobiological technology</td>
</tr>
<tr>
<td></td>
<td>4 ⇔ 40</td>
<td>Radiotherapy</td>
</tr>
</tbody>
</table>

Table 1.
In Table 1, direct applications of electron beams are listed. On the other hand, applications due to beam induced radiation, such as Bremsstrahlung, synchrotron and SASE-FEL radiation, are reported in Table 2.

<table>
<thead>
<tr>
<th>Types of radiation</th>
<th>Energy application (MeV)</th>
<th>Characteristic</th>
</tr>
</thead>
<tbody>
<tr>
<td>ELECTRON BEAM-INDUCED RADIATION</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bremsstrahlung</td>
<td>1 ⇔ 10</td>
<td>sterilization of medical devices</td>
</tr>
<tr>
<td></td>
<td>0.1 ⇔ 40</td>
<td>Radiotherapy</td>
</tr>
<tr>
<td>Syncrotron Radiation</td>
<td>10000</td>
<td>Surfaces Analysis, spectroscopy</td>
</tr>
<tr>
<td>SASE-FEL Radiation</td>
<td>0.1 ⇔ 15000</td>
<td>ricerca scientifica</td>
</tr>
</tbody>
</table>

Tabella 2.

5.2 Electron beams

Electrons, also referred to as $\beta$ rays, are a kind of electromagnetic radiation able to penetrate a few centimeters-thick layer of air or a thin paper. Over the last few years, huge developments in medial applications have been achieved due to this type of radiation, e.g. treatment of biological tissues.

By the term absorbed $Dose D$, one usually refers to the ratio between the average energy released to a volume of matter and the mass of the matter inside the volume.
The Dose $D$ is measured in gray $Gy$. One gray corresponds to the absorption of one Joule from one Kg of matter.

Irradiation with $X$ rays of biological tissues causes an inevitable damage to the irradiated area since the intensity of the absorbed dose cannot be localized. On the other hand, $\alpha$ rays (protons) show a larger penetration depth and the energy deposition happens in a smaller area (Bragg Peak), leaving undamaged the healthy tissues. Protons with an energy of 200 MeV are sufficient to reach any internal organ. The released dose as a function of the penetration depth for certain radiations is shown in Fig. (5.1).

![Figure 5.1: Penetration depth of the Radiation](image)

Electron beams are by far preferred to $X$ rays in superficial irradiation because the energy release by $\beta$ rays (about 20 MeV) decreases to zero after only a 10 – 15 cm depth. Their penetration can be varied by changing the beam energy from outside. Thus, electron therapy is used to treat tumor sites that are located at the skin surface. Nevertheless, certain specifications are required in order to use $\beta$ radiation in medical application:

- small transverse cross-section of the electron beam, *spot size*, so that
localized cancer cells can be treated,

- the flexibility of changing the energy of the radiation from outside the patient, as said above,

- compactness of the device used as source of the electron beams, in order to avoid excessive space in the treatment room,

- easy portability.

All of the above specifications can be achieved by using a hybrid photoinjector, i.e. an accelerating structure fed by an RF power source, with changeable intensity, that produces low emittance electron beams. A hybrid photoinjector working in X-band is object of the present chapter.

5.3 X rays

X rays are commonly generated by Bremsstrahlung, i.e. hitting heavy ion targets with electrons obtained from particle accelerators. High intensity X rays are usually produced in synchrotrons, where the radiation is emitted by electron beams in circular motion. So far, this high intensity radiation is only used for scientific research.

5.4 SASE-FEL radiation

Fourth generation light sources produce what it is known as SASE-FEL (self amplified spontaneous emission-free electron laser) radiation. This kind of radiation, in the visible and X rays range, is highly coherent and it is obtained by electron beams with very high brightness. These electrons are accelerated in a Linac and forced to pass through a wiggler where coherent radiation is emitted.
5.5 Hybrid Compact Photoinjector in X-band for electron beams

The disadvantage of the Bremsstrahlung radiation for medical applications is that the energy spectrum is too wide and the irradiated photon beam doesn’t have good directionality. An improved quality of the radiation can be obtained through third generation light sources (synchrotrons). Nevertheless, it is possible to find an alternative way by using Thomson scattering between a laser beam and relativistic electrons, produced by linear accelerators.

As explained above, monochromatic and low emittance photon beams are necessary to obtain high quality in images for diagnostics, because it will increase the resolution and contrast. In phototherapy, the excitation of metals situated in cancer sites can induce damages due to secondary ionization radiation. Thus, the use of a device able to generate beams that are monochromatic and tunable can decrease the quantity of needed dose. Hard X-rays, with an energy between 10 and 80 KeV and with the good properties mentioned so far, can be easily produced by means of a photoinjector in a scheme for inverse Compton or Thomson scattering.

In Fig. (5.2), a basic experimental setup is sketched.

An X-band klystron provides an RF power of 60 MW at 11.424 GHz. The photoinjector in this scheme is represented by an RF Gun, consisting of 6 accelerating cells (the first one is half of the rest). It uses part of the input power, only 16 MW, and the accelerating field on the cathode has a peak of 200 MV/m. Laser pulses in the UV range (λ = 267 nm, 100 fs, 20 µJ) excite the cathode plate and an electron beam with a 0.25 nC charge is generated by photoelectric effect. A solenoid is held around the Gun for emittance compensation. The electron beam achieves an energy of about 7 MeV at the exit of the RF Gun. A 1.05 m long traveling-wave linear accelerating structure (Linac) is located after the Gun to boost the electron beam energy.
up to 60 MeV. At the exit of the Linac, a triplet of magnetic quadrupoles focus the beam so that the transverse dimensions, spotsize, reaches a value of 20 $\mu$m. Once the electrons are outside the accelerating sections and have high energy, they are forced to head-on collision with infrared laser pulses (60 mJ, 50 fs, 10 Hz with a spot of 50 $\mu$m in radius). In such a way, production of X-rays is achieved.

The research and development of accelerating structures in X-band allow to produce hard X-rays that are tunable and monochromatic. Also, X-band devices have reduced geometric dimensions with the possibility of reaching higher accelerating field gradients.

### 5.6 Hybrid Compact Photoinjector

The classic configuration of a photoinjector consists of two accelerating structures axially alignment: an RF Gun (Standing wave) and a Linear accelerator (Linac). The electron beam, generated at the cathode of the RF Gun, gains
enough energy to become relativistic, usually 5 MeV, and is thus injected into the Linac where it propagates while gaining extra energy. A beam tube separates the two structures and its length is such that the beam undergoes the emittance compensation process [24]. RF Power is transported to both the gun and the Linac independently, in order to protect the source from inevitable reflections from the SW section [see Fig. (5.3)].

Figure 5.3: Scheme of a classic photoinjector.

The design of a compact photoinjector, able to produce high brightness beam in the energy range of 20-30 MeV, brings a huge innovation in the field of photoinjectors:

- the basic scheme, SW and TW is unchanged, but the alignment of the two structures is different; the long beam pipe is replaced by a cell that couples the two structures

- this cell has a double feature: first cell of the TW section and coupler cell of the full photoinjector, since total input power is coupled to it (see Fig. (5.4)).

The main advantages of this new configuration are:
• reduced mismatch, that is low reflected power, between the source and the SW section;

• RF power is provided only through one waveguide;

• reduced dimensions are a considerable benefit to the physical space.

In this chapter, the following tasks will be addressed:

1. RF design of the hybrid compact photoinjector in X-band;

2. fabrication and bench measurements of structure.

### 5.7 RF Design of the photoinjector

The numerical code employed for electromagnetic simulations is HFSS (High Frequency Structures Simulator). The geometric 3D model of the photoin-
jector is given in Fig. (5.5). All geometric parameters needed for the RF design are also shown.

Figure 5.5: 3D Model used for RF simulations.

It has been possible to exploit the symmetry of the structure so that, for simulation purposes, only half of the full device is considered. By doing so, computational time turned out to be faster than the full geometry case.

The accelerating structure can be divided into two parts: a standing-wave (SW), that we can also refer to as the RF Gun and a traveling-wave section (TW). In the ideal case, they are separated by a perfect magnetic boundary (“perfect H”) located at the center of the coupling iris with radius $ac$. This iris causes the axial electric field to cancel at its location, and an area with zero electric field can be represented with a “perfect H”.

In this way, it is possible to draw and proceed to the RF design of the two structures separately. The target for the SW Gun is to achieve a good field balance inside the two cells, requirement known as *fieldflatness*, while for the TW section it is important that power reflections at the input waveguide port are eliminated, i.e. reflection coefficient equal to zero. The final step is
to eventually unite the two sections and adequately apply some modifications in order to keep the RF Gun on resonance and the desired field profile.

The main technical requirements that the RF design has to respect are the following: correct length $d_c$ of the coupling cell, also called coupler cell, and geometric dimensions of the coupling iris (i.e. radius $a_c$ and thickness $t_c$) in order to obtain a certain ratio between the accelerating field amplitudes in both sections ($|E_{z,SW}/E_{z,TW}|$); correct phase of the axial field $E_z$ in order to properly accelerate the electron beams. The value of the fields ratio is determined by dynamics studies of the particles inside the photoinjector that have to satisfy certain properties, such as low emittance, as discussed in section 5.2. It’s been noticed that a value in the range from 4 to 5 is necessary, even if a value of 3 has been considered reasonable. As far as the phase is concerned, following are the choices that have been made:

1. the Gun consists of one full cell and a half cell operating in the $\pi$ resonant mode,

2. the TW section operates in the $2\pi/3$ accelerating mode.

The resonant frequency of the full system is in X-band, 11.424 GHz. From point 1, one derives the length of the full SW cell equal to $d_f = \lambda/2 \approx 13.12$. Plus, the length of the TW cell can be derived from point 2 and is equal to $d = \lambda/3 \approx 8.747$, assuming relativistic the particles entering the TW section (see chapter 2 for details).

### 5.7.1 Choice of the length $d_c$

The value of the length $d_c$ of the coupler cell follows from assumptions on the electromagnetic field inside the photoinjector. As in any structure with cylindrical symmetry, the axial electric field, along $z$ in the present case, is described by the following general expression:
\[ E_z(z,t) = E_0(z) \cos(\omega_{RF}t + \Phi(z)) \]  

(5.1)

where \( E_0(z) \) and \( \Phi(z) \) are the amplitude and the phase of the accelerating field, respectively.

An important issue, that will be exploited in this section, concerns a result that was obtained in the RF design of a similar photoinjector in S-band, 2.856 GHz [18]: the phase difference \( \Delta \Phi \) between the coupler cell and the SW section turns out to be constantly equal to \( \pi/2 \), whenever the Gun is at resonance, that is the working frequency. Keeping this result in mind, we’ll discuss about two options for the length \( dc \). The first one simply assumes the the coupler cell is part of the TW section, as it usually is considered, thus its length is equal to the other TW cells. In this case, because of the \( \pi/2 \) phase shift, no continuous acceleration is verified in the transition from the Gun to the TW part, that is the particle is not always at a maximum electric field value. Nevertheless, the injection into the positive slope of the field causes what it is well-known as "Velocity Bunching" (VB). The photoinjector in the VB configuration is what best suites beam dynamics requirements in term of beam parameters such as low-emittance and small spotsize. Indeed, it is exactly the VB hybrid photoinjector that has been fabricated at INFN-LNF in Frascati and whose experimental results are part of this thesis and discussed further on. The second option, on the other hand, implies that continuous acceleration (CA) is kept between the two accelerating parts. In order to derive the length \( dc \) in this case, a theoretical consideration is needed. Let us consider a particle in the center of the SW full cell at the time when the axial electric field is maximum, that technically it is the case when the particle is on crest. The time \( t^* \) needed by the particle to reach the center of the coupler cell has to be such that the particle is on crest of the electric field again. The quantity \( t^* \), "time of flight", is defined as
\[ t^* = \frac{df/2 + dc + d/2}{c} \quad (5.2) \]

where \( c \) is the speed of light. We assume that the electrons are relativistic at the exit of the Gun. As discussed above in the previous section, \( df = \lambda/2 \) and \( d = \lambda/3 \), the time of flight \( t^* \) is obtained by implying:

\[ E_0 = E_0 \cos(\omega_{RF} t^* + \Delta \phi^*) \quad (5.3) \]

considering expression (5.1) and the definition (5.2).

The quantity \( \Delta \phi^* \) is equal to \( \pi + \pi/2 - 2\pi/3 = -\pi/6 \), that plugged into (5.2) gives:

\[ \omega_{RF} t^* - \pi/6 = 2K\pi \quad (5.4) \]

where \( K \) is an integer. Set \( K = 1 \), we obtain:

\[ \omega_{RF} t^* - \pi/6 = \frac{2\pi c}{\lambda} \quad t^* - \pi/6 = 2\pi \quad \Rightarrow \quad t^* = \frac{13\lambda}{12c} \quad (5.5) \]

that plugged into (5.2) gives

\[ dc = \frac{2}{3} \lambda. \quad (5.6) \]

Finally, the value obtained for \( dc \approx 17.494 \) mm.

### 5.7.2 Choice of iris thickness and radius

The traveling-wave section is basically a circular waveguide loaded with metallic discs of thickness \( t \). The irises with a radius \( a \) are the holes through which the \( TM_{01} \), of an equivalent circular waveguide, propagates. After taking into account characteristic results for TW Linacs, also mentioned in chapter 2, we chose:

- \( a = 4 \) mm,
• $t = 2$ mm.

while for the SW structure:

• $ag = 3.1$ mm,

• $tc = tg = 4.76$ mm.

### 5.7.3 Geometric dimensions of the input waveguide

A X-band standard rectangular waveguide is used to fed the RF power into the photoinjector through the coupler cell. The geometric dimensions are:

• $aw = 10.16$ mm,

• $bw = 22.86$ mm.

All of the other dimensions are given in the following sections, since derived from optimization methods achieved by using numerical codes like HFSS. The full structure of X-band hybrid photoinjector is shown in Fig. (5.6).

![Figure 5.6: Full structure of X-band hybrid photoinjector.](image-url)
5.8 RF design of the standing-wave structure

An RF Gun is a multicell standing-wave structure. Usually, the first cell is half in length with respect to the subsequent cells. The reason why is that, in such a way, the longitudinal electric field is at its maximum value, for a certain phase, at the initial wall (the cathode plate). As a consequence, the particle beam is accelerated properly as soon as it enters the structure. In this section, we expose the results obtained for the RF design of the Gun, consisting of one full cell and one half cell, carried out by using the code HFSS. A transverse view of the model used for simulations is shown in Fig. (5.7).

![Transverse view of the standing-wave structure.](image)

The material chosen for the surfaces of Gun is copper and a boundary condition of “perfect H” is imposed at the half-iris location, so that a zero magnetic field is obtained.

The design mainly follows two steps:

- choice of geometric dimensions in order to set the cavity resonant frequency at \( f_\pi = 11.424 \) GHz, in the \( \pi \)-mode operation,

- achievement of a field flatness condition, that is balance of the field amplitude in the Gun cells.
The quantity field flatness, that we’ll refer to as ff further on, can be defined as \( ff = \frac{E_m}{E_M} \cdot 100\% \), where \( E_m \) and \( E_M \) are the minimum and maximum value of the axial electric field. The algorithm used for the achievement of the specifications listed above employs a linear system of partial differential equations, solved iteratively as follows:

\[
\frac{\partial ff}{\partial R_h} \Delta R_h + \frac{\partial ff}{\partial R_f} \Delta R_f = \Delta ff; \tag{5.7}
\]

\[
\frac{\partial f_\pi}{\partial R_h} \Delta R_h + \frac{\partial f_\pi}{\partial R_f} \Delta R_f = \Delta f_0; \tag{5.8}
\]

where the differential terms represent the sensitivity of the field flatness and the resonant frequency \( f_\pi \) with respect to the radii \( R_h \) and \( R_f \). These radii are considered the only geometric variables in order to speed the solution of the system, thus they are the unknowns of the system. The \( \Delta ff \) and \( \Delta f_\pi \) are the differences between the values obtained at each iteration and the required ones:

\[
\Delta ff = ff_{iteration} - ff_{optimum}; \tag{5.9}
\]

\[
\Delta f_0 = f_{iteration} - f_{optimum}; \tag{5.10}
\]

where we assume \( ff_{optimum} = 1 \) e \( f_{optimum} = 11.424 \).

After few iterations, we obtain the following results: \( R_h = 10.411 \) mm and \( R_f = 10.423 \) mm. In Figg. (5.8) and (5.9), the amplitude and phase of the axial electric field are plotted by using the new radii: the resonant frequency is at 11.424 GHz and the phase shift between the two cells assures the build-up of the \( \pi \) mode.
5.9 RF design of the traveling-wave structure

The traveling-wave accelerating section is a periodic structure with period $d$. The RF power is fed with a standard X-band waveguide through the coupler cell. The electromagnetic mode excited is similar to the $TM_{01}$ in a circular waveguide. Its phase advance per cell is $120^\circ$, thus it is usually called $2\pi/3$-mode. The power flows along the structure inside the middle cells, or main cells, and after reaching the end it is damped into a matched load through
another coupler cell. The main cell, whose design is discussed in this section, is shown in Fig. (5.10).

Figure 5.10: Single main cell of the traveling-wave structure.

The code HFSS allows to simulate periodic structures by only using one period and applying proper boundary conditions. The condition “Master/Slave” enables to impose a phase shift, $120^\circ$ for the photoinjector case, between two faces of the single cell. Then, a simulation with the eigen-mode solver finds the frequency at which the electromagnetic field satisfies the phase shift desired. The power of this process consists in that it is possible to run the cell as it were standing-wave so that no coupling from the outside is needed. It is fast and accurate. In order to tune the frequency, the radii of the cell can be adjusted, since the length $d$ of the cell is fixed by the type of electromagnetic mode. Exploiting the symmetry in the field, only one quarter of the full cell is used for simulations and a condition of perfect magnetic boundary, called “perfect H”, is applied, as shown in Fig.(5.11).

Once the design for the single main cell has been optimized, next step is the dimensioning of the coupler cell.
5.10 Design of the Coupler cell: the “method of the shorts”

An important specification, after project frequency (11.424 GHz) and the propagating mode \((2\pi/3)\), is the value of the reflection coefficient \(\Gamma\) at the input port. One usually requires \(\Gamma\) to assume a value very close to zero, in linear units. For the hybrid photoinjector, the requirement on the reflection coefficient is assumed to be \(\Gamma < 0.1\), that is a reasonable number for our purposes. This means that the tolerance on the reflected RF power is less than 1%. The input power flows into the coupler cell through a small hole, usually denominated “coupling slot”. The main two geometric parameters that allow to adjust the reflection coefficient are the radius of the coupler cell \(R_c\) and the width of the coupling slot \(w\). The choice of \(R_c\) and \(w\) is made by applying the “method of the shorts” [19], whose explanation and implementation are explained below. The structure in Fig. (5.12) represents the input waveguide attached to the coupler plus a half cell, that we consider as part of the coupler cell, closed with a short (corresponding to “Perfect-E” boundary condition). From simulation, we obtain a reflection coefficient at the input port equal to \(\Gamma_{sc}^{(0)}\), having unitary amplitude and a certain phase.
In order for the reflection coefficient $\Gamma$ to be zero, the following steps have to be satisfy:

- if another cell is attached to the initial configuration, see Fig. (5.12), and the same simulation as before is run, we obtain a reflection coefficient $\Gamma_{sc}^{(1)}$ shifted by $-240^\circ$ with respect to the previous one;

- again, if another cell is attached, see Fig. (5.13), we obtain a reflection coefficient $\Gamma_{sc}^{(2)}$ shifted by $-240^\circ$ with respect to the previous one.

![Figure 5.12: to the left, coupler cell with 0 cell attached; to the right, coupler cell with 1 main cell attached.](image)

If the reflection coefficient $\Gamma$ is zero, then the three coefficients calculated above lay on the complex plane at the vertices of an equilateral triangle inscribed in a circle of unit radius. From now on, we will use the following definitions:

$$\alpha = \phi \left( \frac{\Gamma_{sc}^{(1)}}{\Gamma_{sc}^{(0)}} \right)$$

$$\beta = \phi \left( \frac{\Gamma_{sc}^{(2)}}{\Gamma_{sc}^{(1)}} \right).$$

(5.11) (5.12)
An algorithm has been implemented in order to optimize the coupler cell design. It makes use of a linear system of partial differential equations, solved iteratively, as follows:

\[
\begin{align*}
\partial \alpha \frac{\partial \Delta R_c}{\partial R_c} + \partial \alpha \frac{\partial \Delta w}{\partial w} &= \Delta \alpha \\
\partial \beta \frac{\partial \Delta R_c}{\partial R_c} + \partial \beta \frac{\partial \Delta w}{\partial w} &= \Delta \beta
\end{align*}
\]  

(5.13) \hspace{1cm} (5.14)

where the differential terms represent the sensitivity of the parameter \( \alpha \) and \( \beta \) with respect to the radius \( R_c \) and the coupling slot width \( w \), see Fig.(5.14). \( R_c \) and \( w \) are considered the only geometric variables in order to speed the solution of the system, thus they are the unknowns. The quantities \( \Delta \alpha \) and \( \Delta \beta \) are the differences between the values obtained at each iteration and the required ones:

\[
\begin{align*}
\Delta \alpha &= -240 - \alpha \\
\Delta \beta &= -240 - \beta.
\end{align*}
\]  

(5.15) \hspace{1cm} (5.16)
5.11 Results of the “method of the shorts”

It has been possible to achieve the specs for the traveling-wave structure by using the method described above. The following values for $R_c$ and $w$ have been found:

- $R_c = 10.13$ mm,
- $w = 8.05$ mm,

The reflection coefficient $\Gamma$ at the input waveguide is plotted in Fig. (5.15).

The RF Gun is attached to the traveling-wave part through the coupling iris with radius $a_c$ and directly to the input coupler cell. As mentioned previously, another coupler cell is present at the exit of the TW section, through which the RF power is damped into a matching load. The geometric dimensions of the output coupler are fixed and unmodified throughout the whole process of optimization of the full photoinjector. The reason why is that a traveling-wave accelerator acts like a uniform waveguide, reciprocal and lossless in the present case, thus the transmission coefficient $s_{12}$ of the
photoinjector only depends on $\Gamma$, or $s_{11}$, i.e. the input coupler. In this regard, the relationship between the two coefficients is the following:

$$|s_{12}| = \sqrt{1 - |s_{11}|^2},$$  \hspace{1cm} (5.17)

thus, it is evident the transfer of power through the structure only depends on the input.

In Fig. (5.16), the amplitude and phase of the electric field along the $z$-axis are reported. We notice a difference between the amplitude of the field inside the coupler cells and the main cells. This is due to the fact that the radius $R_c$, obtained after an optimization process, results to be smaller than the radius of the main cell $b$. Nevertheless, a perfect field flatness is achieved inside the main cells, that represent the actual traveling-wave section of the photoinjector, in which the electrons are primarily accelerated.
Figure 5.16: above, amplitude of the on-axis electric field; below, phase of the on-axis electric field inside the TW section.

5.12 RF design of the full accelerating structure

The design of the SW and TW sections has been carried out so far. At this point, the two structure are aligned and attached so that the RF design of the full structure, the photoinjector, can be performed. The 3D model is given in Fig. (5.17).

The union of the two separate sections raises two main drawbacks, as
Figure 5.17: 3D model of the photoinjector from HFSS

expected:

1. variation in the reflection coefficient $\Gamma$, that from a value close to zero has shifted to 0.07 at the project frequency $f_\pi = 11.424$ GHz.

2. detuning of the Gun, leading to a zero electric field at the frequency $f_\pi$, as shown in Fig. (5.18).

Point 1 doesn’t need much attention since it still satisfy the specification, as discussed in a previous section ($\Gamma < 0.1$). Through the following sections, we’ll deal with point 2 since, according to the requirements, the amplitude of the field inside the SW cells has to be higher than inside the TW cavities. Even though the Gun has been designed to resonate at the desired frequency, the reason why the field inside is zero is due to a frequency shift caused by the attachment of the SW part to the TW one. Thus, next target is the re-tuning the RF Gun.
5.13 Tuning of the RF Gun

An SMA antenna, very small, is used as a probe inside the Gun and is positioned in the cathode plate, though a small hole, in a location such that it is able to excite the electromagnetic field inside the cavity but, at the same time, not to alter the field distribution.

In the simulations carried out with HFSS with the “driven solution” solver, three ports have been defined, as shown in Fig. (5.19). From now on, the reflection coefficient at the waveguide input (port 2) $\Gamma$ will be indicated as $s_{22}$, just to avoid confusion.

Once the RF power from the input waveguide excites the field inside the photoinjector, the easiest way to know the frequency that the Gun resonates at is to obtain the transmission coefficient between port 1 and port 2. This coefficient is known as the $s_{12}$ and it is provided by HFSS, after performing a frequency sweep around the solution frequency. The transmission coefficient $s_{12}$ is plotted in Fig. (5.20): the two peaks refer to the 0-mode with frequency
Figure 5.19: *Photoinjector Model with introduction of three ports.*

$f_1$ and the $\pi$-mode with frequency $f_2$, representing the two resonant modes inside the one and a half-cell Gun.

Figure 5.20: *Amplitude of the transmission coefficient $s_{12}$ as a function of the frequency*

From the picture, it is obvious that the frequency of the mode of interest, $f_2$, has been shifted downward of about 2 MHz (11.4228 GHz) that in X-band can be seen as a big number.

By setting the frequency of the input RF power, port 2, at the frequency
We observe what it was expected: the plot of the axial electric field for the new frequency assures that the SW section is actually on resonance, see Fig. (5.21).

Figure 5.21: Amplitude of the axial electric field $E_z$ [V/m] and of the phase at the resonance frequency of the Gun $f_2 = 11.4228 \text{ GHz}$

It is evident then that $f_2$ is the frequency which the full structure needs to be tuned at. In the next subsection, a method for achieving the frequency change is explained. By looking at the graph of the phase of the electric field in Fig. (5.21), it turns out that also in the case of the photoinjector at 11.424 GHz, the phase shift between the second and third cell of the full structure
is equal to 90°. This was already discussed in section 5.7.1.

5.13.1 Adjustment of the Gun cell radii

A way to change the resonant frequency of the Gun is to vary the dimensions of the cells radii. All other dimensions can remain unmodified. For the following values:

- $R_h = 10.41$ mm
- $R_f = 10.425$ mm

the plots of the $s_{12}$ and $s_{22}$ coefficients are reported in the same Fig. (5.22). We notice a positive shift in the frequency $f_2$, i.e. $f_2 = 11.427$ GHz while the frequency corresponding to a minimum value of the reflection coefficient at port 2 moved slightly downward with respect to the case in Fig. (5.15).

![Figure 5.22: Amplitude of the coefficients $s_{12}$ and $s_{22}$](image)

The value of the $|s_{22}|$ at the frequency $f_2 = 11.427$ GHz is equal to 0.05, in agreement with the project specifications. The amplitude of the longitudinal
electric field is given in Fig. (5.23). The ratio between the field peak in the Gun and the peak field in the TW section is about 2, too low for the project specs that require about $3 \div 4$. Nevertheless, it has been possible to modify this ratio, as explained in section 5.14. On the other hand, the phase shift $\Delta \Phi_{23}$ is constantly equal to $90^\circ$.

![Figure 5.23: Amplitude of the axial electric field $E_z$ [V/m] at the frequency $f_2 = 11.427$ GHz.](image)

5.14 Adjustment of the coupling iris

In order to enhance the amplitude of the field inside the SW section, the radius $ac$ of the coupling iris has been increased. By doing so, the fraction of power flowing from the input waveguide towards the Gun is larger. The new value used is $ac = 2.7$ mm. Such adjustment requires that the two structures, SW and TW, to be simulate again, separately. This means to apply the algorithm discussed in section (5.8) for the SW part and the method of the shorts for the TW one. The optimization results are the following:

- $Rh = 10.411$ mm,
• $R_f = 10.468 \text{ mm},$

• $R_c = 10.16 \text{ mm}.$

Figure 5.24: Amplitude of the coefficients $s_{12}$ and $s_{22}.$

Figure 5.25: Amplitude of the axial electric field $E_z [\text{V/m}]$ at the frequency $f_2 = 11.422 \text{ GHz}.$
The plot of the $s_{12}$ and $s_{22}$ coefficients is shown in Fig. (5.24), while the accelerating electric field is given in Fig. (5.25). It has to be noticed that the ratio $E_{zSW}/E_{zTW}$ has been increased noticeably. In particular, we have obtained the following results:

- $f_2 \approx 11.422$,
- $s_{22}|_{f_2} \approx 0.09$,
- $|E_{zSW}/E_{zTW}| \approx 4.5$.

5.15 Final tuning of the RF Gun

The value of the frequency $f_2$, discussed in the last section, is slightly lower than project specification. The goal if to shift $f_2$ so that $f_2 = f_0 = 11.424$ GHz, at which the reflection coefficient $s_{22}$ has to reach its minimum value. As discussed in previous sections, the $s_{22}$ already shows low values around the project frequency. Thus, we proceed to tune the frequency by adjusting the SW radii. Using the value $b_f = 10.465$ mm, we obtain a resonance at $f_2 = 11.4244$ GHz, that satisfies the specs. Nevertheless, a change non negligible is observed in the reflection coefficient. It follows that it is not possible to achieve the desired value for the resonance frequency and minimum of reflection coefficient at the same time by modifying only the SW section dimensions. It has to be pointed out that a tolerance in the frequency $f_2$ of about $\pm 500$ KHz around $f_0$ can be accepted.

5.16 Choice of the coupler cell geometric parameters

Considering the results obtained in section (5.14) concerning the coupling iris, the parameters of the coupler cell have been modified. In particular,
it has been noticed that a variation of the radius $R_c$ doesn’t cause any improvement in the reflection coefficient, while good results are obtaining by modifying the width $w$ of the coupling slot. Three variations of $w$ are reported in the Table below.

<table>
<thead>
<tr>
<th>$w$ (mm)</th>
<th>$f_2$ (GHz)</th>
<th>$s_{22}/f_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>11.4228</td>
<td>0.09</td>
</tr>
<tr>
<td>7.99</td>
<td>11.4229</td>
<td>0.08</td>
</tr>
<tr>
<td>7.95</td>
<td>11.4228</td>
<td>0.09</td>
</tr>
</tbody>
</table>

As it is evident from the Table, the resonant frequency of the SW section remains almost unchanged while a decrease in the reflection coefficient is obtained, $s_{22}/f_2 = 0.08$ for $w = 7.99$ mm. The correspondent plots of the amplitude and phase of the electric field are reported in Fig. (5.26):

- good flatness of the electric field in the traveling-wave part,
- the field balance of the electric field in the SW section is not perfect, even if it would be useful to have a higher peak at the cathode plate in order to reduce the space charge effects of the beam,
- the ratio $|E_{zSW}/E_{zTW}| \simeq 4.1$ is in good agreement the project specs.

5.17 Sensitivity of the parameter $ac$

In order to fulfill the specification on the ratio $E_{zSW}/E_{zTW}$, the parameter $ac$ has been taken in consideration. In the graph (5.27), the behavior of this ratio as a dependent variable of $ac$, in the range $2.2 - 3$ mm, is shown. It is interesting to notice that for smaller values of $ac$ the ratio varies slowly while it assumes a linear behavior with increasing $ac$.

The quantity that is plotted refers to the optimum condition, obtained by following all the steps in the previous sections for each value of $ac$:
Figure 5.26: Amplitude of the axial electric field $E_z$ [V/m] at the frequency $f_2 = 11.4229$ GHz.

- resonant frequency of the Gun equal to $f_2$,
- low value of the reflection coefficient at the input port and at the frequency $f_2 (s_{2d} f_2)$.

For values of the radius $ac$ below the interval of interest, the quantity $E_{zSW}/E_{zTW}$ is quite constant, until a decoupling between the Gun and the
coupler cell is verified. On the other hand, for values of the radius above the interval, the reflection coefficient $s_{22}$ is extremely perturbed by the standing-wave section so that an optimum condition is never achievable.

5.18 Simulation results for the Photoinjector in VB configuration

The same RF design discussed so far, for the Continuous Acceleration (CA) case, has also been performed for the Photoinjector in Velocity Bunching (VB) configuration.

Figure (5.28) and (5.29) show the amplitude and phase of the on-axis electric field, respectively.

The amplitude of the field has the same behavior as in the case of the Continuous Acceleration (CA) configuration. The main difference to notice is the field magnitude inside the two coupler cells: it shows the same distribution as the main cells, since in VB configuration all the cells have the
same length.

5.19 Measurements on the prototype

The prototype of the photoinjector in VB configuration has been machined at INFN-LNF of Frascati, see Fig. (5.30). The device is made out of copper. Three ports are included: the two waveguides for input/output of the RF power through the TW part, and an SMA antenna located at the cathode
plate for tuning of the SW section.

Figure 5.30: Prototype of the Photoinjector

Bench measurements have been performed at LAR (Laboratorio di Acceleratori e Rivelatori), in the Department of Energetics of the University of Rome “La Sapienza”. The reflection coefficient $S_{11}$ is plotted in fig.(5.31). It shows reasonable RF coupling at $11.424$GHz ($S_{11} \approx -13$dB). In the same plot, we notice the presence of two small peaks due to the SW section. As a matter of fact, these two peaks are located at $f_1 = 11.3839$GHz and $f_2 = 11.4064$GHz and represent the 0 mode and $\pi$ resonant modes inside the SW, respectively. This is also evident from Fig. (5.32) that shows the transmission coefficient $S_{13}$ between input waveguide and SW part and the reflection coefficient of the RF Gun $S_{33}$.

In order to quantify the electric field inside the structure, two different methods have been employed. The Slater Method for the SW cavity and the Steele method for the TW section. The former is a resonant method that only allows to measure the amplitude of the field, the latter is a non-resonant
method and it allows to calculate both amplitude and phase of the field. Equations (5.18) and (5.19) show the relationship between the amplitude $|E|$ and the frequency shift $\Delta \omega$, for the first case, and between the vector $E$ and the reflection coefficient $S_{11}$, in the second case.

\[
|E|^2 = -\left( \frac{4U_0}{\epsilon_0 k_{\text{slater}}} \right) \frac{\Delta \omega}{\omega_0} = -\left( \frac{4U_0}{\epsilon_0 k_{\text{slater}}} \right) \frac{\Delta \Phi_{13}}{2Q_L} \quad (5.18)
\]

\[
E^2 = \frac{2P_{\text{in}}(S_{11p} - S_{11u})}{j\omega k_{\text{steele}}} = \frac{2P_{\text{in}} \Delta S_{11}}{j\omega k_{\text{steele}}} \Rightarrow \left\{ \begin{array}{l}
|E|^2 = |\Delta S_{11}| = \frac{2P_{\text{in}}}{\omega k_{\text{steele}}} \, , \\
\Phi_E = \Phi_{\Delta S_{11}}/2 .
\end{array} \right. (5.19)
\]

where $S_{11p}$ and $S_{11u}$ are respectively the perturbed and unperturbed reflection coefficient $S_{11}$ and $\Delta S_{11} = S_{11p} - S_{11u} = |\Delta S_{11}|e^{j\Phi_{\Delta S_{11}}}$.

A sketch of the measurement setup is given in (5.33). A perturbing object (1 mm in length and 1 mm in diameter) is attached to an horizontal fish lens that lays on the same direction as the axis of the photoinjector. By using
a step-by-step motor, it is possible to pull the wire through the structure and measure the perturbations caused by the small bead. The measurement setup is referred to as “bead-pull”. As explained above, we measure frequency shifts in the SW and variations of the reflection coefficient (Amplitude and Phase) in the TW. All the data, obtained by using a VNA, are stored in a PC via a GPIB.

Figure (5.34) shows a measurement of the axial electric field inside the SW section (Slater method), while figure (5.35) shows a plot of the amplitude (green) and phase (blue) of the axial electric field inside the TW section (Steele Method). Nevertheless, it is possible to measure the field through the whole photoinjector by applying Steele method, because a standing-wave cavity can be thought as a traveling-wave linac with a cell-to-cell phase shift equal to $\pi$.

In Fig. (5.36), it is shown a plot of the axial electric field along the whole structure at the resonant frequency of the SW $\pi$-mode ($f_2 = 11.4064GHz$, 94
i.e. almost 18 MHz below the project frequency).

In order to compare these results with the requirements exposed in section (5.7), we report the features that have been quantified, showing good
agreement:

- $E_{zSW}/E_{zTW} = 2.5 \rightarrow 2.03$ (measured)

- Phase advance per cell $120^\circ \rightarrow 118^\circ$ (measured)

- Field balance inside TW (100%) $\rightarrow 70\%$ (measured)
The above characteristics are also reported in Fig. (5.36).

A frequency scan has been performed, in order to search for the frequency where the required phase difference is achieved. The dispersion curve of the sweep is plotted in figure (5.37). It is evident that a phase shift of about 120° is reached at $f = 11.414GHz$, that is 10 MHz below the project frequency.

By plotting the field at this new frequency, we observe that the desired mode inside the TW structure shows the expected behavior while the field inside the SW is absent. This means that is necessary to proceed with a tuning process of the standing-wave cavity. In such a way, it will be possible to shift the resonant frequency to the desired one of the $2\pi/3$ inside the TW. The two frequencies must match. To this end, the presence of a small antenna on the cathode plate of the SW allows to track this procedure. At the same time, by tuning the TW cells it is also possible to adjust the frequency of the $2\pi/3$ mode in order to be close to the required one, $f = 11.424GHz$.

![Dispersion curve](image.png)

**Figure 5.37: Dispersion curve**

Finally, we compare the experimental results from measurements and simulations carried out with HFSS. Figure (5.38) shows this comparison for the electric field amplitudes. Good agreement is achieved.
Figure 5.38: Comparison between the field amplitude from measurements, above; and from simulations with HFSS, below
Chapter 6

Simulation codes

In this chapter, the numerical codes used for the various simulations, carried out in this thesis work, are briefly explained.

6.1 HFSS

HFSS (High Frequency Structures Simulator) is a user-friendly software package, initially released by ANSOFT [1], Pittsburg, that allows to evaluate the 3D electromagnetic field distribution inside a structure. In order to do this, it solves the Maxwell equations in the frequency domain, so only linear material can be simulated. The numerical method employed is the FEM (Finite Element Method). HFSS divides the 3D model into a relatively large number of small domains, tetrahedra, that represent the mesh. The following features can be obtained from simulations:

- main RF properties of the electromagnetic field, and also the near and far fields for open structures;
- propagation constants and impedance at specified ports;
- parameters of the scattering S-matrix;
• eigenvalues, or resonant frequencies, and eigenfunctions for a closed structure.

6.2 ePhysics

ePhysics [2] is a software package that simulates and solves three-dimensional thermal and structural problems, making use of the finite element method. The useful property of this code is the possibility of the coupling with HFSS. The user-friendly interface allows to easily import a 3D geometry and all the results from an electromagnetic analysis, carried out with HFSS, in order to perform a thermal-stress simulation.

A typical solution process is sketched in Fig.(6.1). Due to Ansoft’s Dynamic Link, this process is fully automatic. Electromagnetic simulations are either performed in frequency domain (HFSS) or magneto-static (Maxwell) and then used as sources for thermal-stress analyses in ePhysics.

The types of solutions supported by ePhysics are the following:

• **Static Thermal** 3D temperature distributions in the steady-state regime with convection and radiation boundary conditions. The source of temperature variation is usually a thermal load or electromagnetic losses in the material used. In the case of electromagnetic losses, the HFSS design with the electromagnetic solution is fully imported into ePhysics.

• **Transient Thermal** (time domain) 3D transient temperature distributions. This module provides temperature variations due to temporal distributions of the sources.

• **Static Stress** (linear static elastic analysis) 3D steady-state deformation and stress states due to mechanical, thermal or electromagnetic loads. The temperature distribution calculate with the Static Thermal
solver can be used as an input in order to obtain a stress analysis of the structure under examination.

![Sketch of a typical solution process](image)

Figure 6.1: *Sketch of a typical solution process*

### 6.3 Parmela

PARMELA (Phase and Radial Motion in Electron Linear Accelerators) [3] is a numerical code that is able to simulate the dynamics of different kinds of particles (electrons, positrons and ions) inside an accelerating structure, such as a Linac (Linear Accelerator) or an RF Gun, i.e., a beam injector. Once the distribution of the electromagnetic field inside the accelerator is provided, PARMELA integrates the particle trajectories inside the field. The field configuration can be supplied from SuperFish for Radio-frequency structures and from Poisson for electro-magnetostatic problems.
6.4 SuperFish

SuperFish [3] is the main solver program for calculating Radio-Frequency electromagnetic fields in either 2-D Cartesian coordinates or axially symmetric cylindrical coordinates. The program generates a triangular mesh fitted to the boundaries of the material in the problem geometry. It is not a very user-friendly code, like HFSS, and the internal part of the structures is simulated independently from any kind of input source. This means that a coupling condition with outside inputs, such as RF waveguide, is not achievable. Nevertheless, the fast computational time of simulations and accuracy of the results make SuperFish a powerful tool for the design of RF accelerators.
Chapter 7

Splitters

In order to divide the power from the input RF waveguide in a dual-feed configuration, as in the case of the RF Gun discussed in Chapter 4, one can employ a “Power Splitter”. The main reason for preferring a dual-feed system instead of a single one resides in the possibility of eliminating the dipole component of the accelerating field. Here, we show the results of the design of a splitter device, performed following the guidelines of LCLS [15], in S-band (2.856 GHz). The 3D model used for the design with HFSS is given in Fig.7.1.

The splitter, or power divider, is a 3-port passive and reciprocal device that equally divides the input power into two identical paths (arms). The total power is eventually recombined in the coupler cell of the accelerating structure. Figure (7.1) also shows a plot of the electric field amplitude distribution inside the splitter. We have to satisfy two requirements: perfect match between the input RF waveguide and the splitter; equally power flow in the arms. These two aspects are accomplished if the reflection coefficient at port 1 is close to zero (linear units, i.e. very low value in dB) and the transmission coefficient between between port 1 and 2, or 1 and 3, is equal to -3dB.

The code HFSS has been used for the simulations. In order to achieve
the requirements, protrusions have been inserted on the splitter walls, as specified in Fig. (7.1). Two of them are located at the input port and a third one at the field splitting point. This is done in order to modify and adjust the scattering coefficients for the desired values at the project frequency. The reflection coefficient, plotted in Fig. (7.2) shows a value of -49dB at 2.856 GHz, operation frequency, ensuring strong coupling and perfect match between the input RF waveguide and the splitter itself.

Figure (7.3) is a plot of the transmission coefficient. As evident, the ratio between input and output power equal to -3dB at 2.856 GHz, i.e. each arm exactly carries half input power.

The same procedure can be followed for the RF design of a splitter in X-band, that we might employ for the Hybrid Compact Photoinjector (see Chapter 5), in dual-feed configuration, shown in Fig. (7.4).
Figure 7.2: Reflection coefficient

Figure 7.3: Transmission coefficient
Figure 7.4: Dual-feed hybrid with input and output splitters.
Chapter 8

Conclusions

The design of the RF gun for the SPARX project has many intersecting elements: RF field optimization and symmetrization, beam dynamics, RF heating (pulsed and average), and thermo-mechanical distortions, and RF performance in the presence of distortions. The study we have reported in this thesis work presents a first pass at addressing all of these design constraints together, with extremely promising results. In the future one may further refine the overall RF design by choosing an even larger radius of curvature for the waveguide coupling iris port structure, to mitigate RF heating. This would also serve to ease the cooling and the mechanical distortion problems in the neighborhood of the iris.

One may also mitigate the overall power dissipated in the RF gun by using a larger coupling, and by using a larger RF drive power. The gun may be filled much more quickly in this way, as discussed by Schmerge [16], resulting in a prospective drop of a factor of 3 in duty cycle, and therefore average RF power. By changing the RF phase and driving the gun out of phase, one might also empty the gun more quickly, diminishing the average power even further. Without considering the details of this final point, we can thus point to a path to operating the RF gun at over 1 kHz. While this is not strictly needed for the present generation of RF guns for FELs such
as SPARX, it would provide a critical component of an optimized inverse Compton scattering source, which naturally may be operated at $\sim 1$ kHz, due to the increasing availability of appropriate laser technology.

We can see that the DMF3 approach can provide wide flexibility in cooling channel design and fabrication, which has already allowed us to consider $1$ kHz RF gun operation. With such innovations as star-shaped cross-sections, and arbitrary channel paths, one can design the cooling system even more aggressively. In this regard, we note that the density of water channels in our preliminary design here is smaller than in many previous attempts at high average power RF gun designs. Thus the tool of conformal, shaped cooling channels has yet to be fully exploited.

The fabrication of the prototype of the RF Gun has been carried out at UCLA (University of Los Angeles, California), in collaboration with the University of Rome “La Sapienza”. The good agreement between experimental results and simulation results has made us more confident in handling new geometries. We refer here to the “race-track” and “Z-coupling” configurations that characterize the coupler cell.

The hybrid compact photoinjector represents a huge step forward in the class of photoinjectors. The already small size (X-band, compact) is further reduced due to elimination of the distance between the standing-wave (SW) and traveling-wave (TW) sections (hybrid feature), that characterizes classic photoinjectors. The use of only one klystron (power source), instead of two for the standard configuration, makes this structure very cost-effective. Furthermore, the elimination of the circulator allows operations with high power, that is a requirement for the generation of hard X-rays, with an energy between 10 and 80 KeV, in a scheme for inverse Compton or Thomson scattering.

The RF design accomplished here for this innovative accelerating device
has shown quite interesting aspects. First of all, the parameter choice of two completely different parts, SW and TW, with different RF characteristics and optimization procedures. The two sections have been designed separately and eventually aligned through a coupler cell. The design of the coupler itself allows two modes of operation: continuous acceleration (CA) and velocity bunching (VB). This feature makes the hybrid photoinjector a versatile device.

The prototype has been machined at INFN-LNF of Fracati. The measurements have been performed at LAR (Laboratorio di Acceleratori e Rivelatori) in the Department of Energetics of the University of Rome “La Sapienza”. Experimental measurements and simulation results have shown good agreement in the electromagnetic field distribution. Frequency wise, the structure has shown high levels of sensitivity that requires the introduction of a tuning system.
Bibliography


[6] Roger H. Miller, Comparison of standing-wave and travelling-wave structures, 2003;


